DISSE

INSTITUTO NACIONAL DE CIÊNCIA E TECNOLOGIA
NANODISPOSITIVOS SEMICONDUTORES

PARTIAL REPORT - YEAR 2009

INCT- SEMICONDUTOR NANODEVICES

I. Management Board

The members of the Management Board are:

Patrícia Lustoza de Souza	PUC-Rio
Paulo Sérgio Soares Guimarães	UFMG
Gustavo Soares Vieira	IEAv
Maurício Pamplona Pires	UFRJ
Nelson Studart	UFSCar

The members responsible for the different missions are:

Paulo Sérgio Soares Guimarães	UFMG	Basic research
Patrícia Lustoza de Souza	PUC-Rio	Technological research
Wagner Nunes Rodrigues	UFMG	Education/training
Nelson Studart	UFSCar	Transfer of knowledge to society
Gustavo Soares Vieira	IEAv	Transfer of knowledge to industry and to government offices

The Management Board together with the responsible members for the different missions have met three times in 2009 at PUC-Rio, the headquarters of INCT-DISSE, to discuss and make a follow-up on the activities of the Institute. Since altogether there are six people only in both groups, the meetings were very productive and we could discuss all the important issues rather efficiently. In the meeting short summaries of the activities were evaluated, the difficulties were discussed and decisions were made on how to treat the problems which arose. In general the meetings run quite smoothly and we always had enough time to discuss the scientific results and mechanisms of knowledge transfer to industry and to society. There was always a constant communication between the members of the Institute via Skype, and therefore, the discussions easily converged.

There has not been any significant change in the goals for the INCT-DISSE. Due to the lack of a fixed schedule for the cash flow, some choices had to be made concerning the application of the received resources. It has been decided that the first payment from CNPq (in fact, the first two) would be used to buy an atomic force microscope for the group at UNIFAP in Amapá because we understand that this group could not work at all without this equipment, since their members are just starting to set up a laboratory. The second priority was given to the group at the University of São Paulo because, in order to work on infrared photodetectors, they needed a Fourier transform spectrometer to routinely characterize the devices, speeding up their research. As a third priority, the theoretical group needed equipment to perform dynamic calculations to better model the performance of the photodetectors developed within the INCT-DISSE. The resources of the last payment in 2009, equipment for time-resolved optical experiments with resonant excitation were bought for UFMG. This equipment is essential to start most of the activities on the fourth topic of research of the Institute, namely, *New physical phenomena in semiconductor quantum dots for innovative opto-electronic devices.*

As for the resources coming from Faperj, they were mainly used to buy the equipment for sample deposition by metalorganic vapor phase epitaxy (MOVPE) and to build the facilities for its installation, as planned. Minor expenses have been routinely made with trips to perform experiments, participation in conferences and meetings, acquisition of consumables and performance of small services.

In the project submitted to CNPq, around US$ 1,500,000.00 have been requested to buy the MOVPE machine. As the budget suffered considerable cuts and this equipment is crucial to the success of the INCT-DISSE, we have put major efforts into receiving extra funds from other sponsors. FINEP has granted us funds to cover about 50% of the costs of this equipment. This grant together with internal rearrangements made the acquisition of the MOVPE machine possible.

II. Co-operation between the groups within the INCT-DISSE

All the groups involved in the INCT co-operate intensely. PUC-Rio and USP supply III-V semiconductor samples to all the experimental groups, namely: UFRJ, UFMG, IEAv, USP, UFAM e PUC-Rio. UNIFAP has not yet received samples because its researchers have just received the equipment necessary to start the investigation, which is now being installed. It should be pointed out that the development of optoelectronic devices involves the use of different experimental set-ups which are spread among the various groups within INCT-DISSE. Therefore, there has been a constant and dynamic collaboration with researchers travelling to different laboratories to perform measurements or to process and fabricate samples. Sometimes the samples travel around and the results are later discussed via Skype or in small meetings.

The theoretical groups from Federal University of São Carlos and Unicamp, Limeira meet regularly, twice a month on the average, to make calculations and to discuss the obtained results. They keep a constant direct contact with the experimentalists to better understand their needs, to exchange parameters to be modeled, to compare the theoretical predictions with the data extracted from the experiments and to set the subsequent goals. The theoreticians involved in the simulation of the growth of self-assembled quantum dots also meet regularly at PUC-Rio and keep a close collaboration with other groups from PUC-Rio and with the group from the Federal University of Rio de Janeiro.

All the members of INCT-DISSE, with the exception of the USP group, coordinated by Professor Alain Quivy, have co-authored publications, demonstrating an effective co-operation. The co-operation with the group of Professor Alain Quivy has started with the foundation of the INCT-DISSE, therefore, there has not yet been enough time to reach publishable results. Surely, soon, there will be publication in co-authorship.

We have recently installed our intranet on the institute webpage which allows the exchange of data, interesting literature items and all sorts of experiences which we consider valuable for the Institute.

III. Co-operation with other INCTs and other institutions

In the field of optoelectronic devices we keep a strong collaboration with the INCT for Photonics and Optical Communication (INCT-FOTONICOM) through Professor Newton Frateschi. We have contributed with the fabrication of semiconductor structures for the development of laser diodes. Additionally, the head of the INCT-DISSE has made a presentation on the activities of DISSE during a workshop organized by the FOTONICOM in March 2009.

A continuous and fruitful collaboration exists in the field of growth of quantum dots on pre-patterned substrates with nanoidentations made by atomic force microscopy with the group of Professor Rodrigo Prioli who is a member of the INCT on Micro- and Nano- electronics (INCT-NAMITEC). This collaboration resulted in a few publications in co-authorship and an article entitled *Growth of linearly ordered arrays of InAs nanocrystals on scratched InP* has been recently accepted for publication in the Journal of Applied Physics. Also, the head of INCT-DISSE has given an invited scientific talk and has participated on a debate about the perspectives and important issues related to the INCTs during a workshop organized by NAMITEC in February 2010. The group of Professor Davies William Monteiro from EE at the Federal University of Minas Gerais maintains an intense co-operation with several members of NAMITEC. They have together organized two events. First, the International Symposium on Microelectronics Technology and Devices – SBMicro, as part of the International Conference Chip on the Dunes in natal from August 31st to September 3rd, 2009 and the IEEE/CASS Workshop on Image Sensors in November 2009. The group has always been invited to participate in the annual meeting of NAMITEC for discussions on photodetectors electronics and mounting.

We have also been collaborating with the group of Professor Jean Pierre von der Weid, member of the INCT on Quantum Information, in the development of photodetectors for free space optical communication. The collaboration is mainly on field tests for such detectors.

Finally, there exists a long term collaboration of the members of DISSE from the Federal University of Minas Gerais with the group of Professor Luiz Cury, member of the INCT- Molecular Electronics, in the development of organic light emitting diodes and phototransistors.

A major part of the members of DISSE is involved in a project co-sponsored by FINEP and the company Invent-Vision (http://www.inventvision.com.br) for the development of infrared photodetectors for industrial inspection. In 2009 the group from LNMS-USP started a collaboration with the company OPTOVAC (http://www.optovac.com.br) for the development of infrared photodetectors for medical and agricultural applications.

Along the year of 2009, in addition to the partnerships already established, several companies which could have an interest in the photodetectors developed by DISSE were contacted. Among them are: Equatorial Sistemas S.A., Opto Eletrônica S.A., Furnas Centrais Elétricas S.A., Embraer - Empresa Brasileira de Aeronáutica S.A. and Petrobras S.A.

Our work on photodetectors and our competence received visibility during two workshops which have greatly benefited from the participation of many companies in the field. The II Workshop on Effects of Ionizing Radiation on Electronic and Photonic Devices for Space Applications, co-organized by members of DISSE from IEAv, took place in October 2009. In November 2009, some members of DISSE participated in the Workshop on Infrared Technologies. The companies which have been contacted during these two events were: Equatorial Sistemas S.A., OMNISYS Engenharia, SMDH – Santa Maria Design House, Opto Eletrônica S.A., EQE Tecnologia, Mosaico Engenharia, OPTOVAC, FURNAS and Thermotronics, as well as institutions such as: CTI, IME, CENPES, COPPE and ITA which have straight ties to industry and government offices.

The international partnerships continued, as described in the original project. In February 2009 the head of DISSE spent a few weeks in Vienna, Austria, continuing the long term collaboration with the TU-Wien in the field of QDIPs. She has closely followed the work of the Ph.D student Thomas Gebhard from Vienna, who is writing his thesis at this point. In the same occasion the Ph. D. student Déborah Reis Alvarenga, co-supervised by Professor Paulo Sérgio Soares Guimarães from UFMG and Professor Patrícia Lustoza de Souza, was at the TU-Wien on an internship. Therefore, it was also possible to give this student extra guidance on her work.

In January 2009 Professor Paulo Sérgio Soares Guimarães was at the TU-Wien and at the University of Sheffield for scientific visits to continue the collaboration with these institutions. Still in July 2009 he has returned to Sheffield to discuss important results on the fourth research topic of DISSE, *New physical phenomena in semiconductor quantum dots for novel devices*, in particular on effects of quantum electrodynamics and photonic crystals.

In July 2009 Professor Paulo Sérgio Soares Guimarães was at the University of Antióquia in Colombia visiting the theoretical group of Professors Boris Rodrigues and Herbert Vinck Posada. His group maintains a close collaboration with Colombia through a bilateral agreement between CNPq and COLCIENCIAS.

IV. Main scientific and technical results

1) Development of infrared detectors in the 2 e 20 μm range for different applications

- ***Theoretical modelling***

The first step in the development of quantum dot infrared photodetectors is the realization of theoretical calculations. We had already planned to use the *split-operator* technique to help understanding the experimental results and also in the design of new structures. Therefore, to start with, we undertook a review of how to use a powerful computational technique, a modified version of the *split-operator* method, to obtain the quantum states of several semiconductor structures. This review is particularly significant for our research group because it describes in detail the method that is being used in the simulations of the nanostructures which will be used for the fabrication of the infrared detectors. This work has given rise to the following publication: *Numerical calculations of the Quantum States in Semiconductor Nanostructures*, Marcos H. Degani e Marcelo Z. Maialle, *Journal of Computational and Theoretical Nanoscience* **7**, 1–20, (2010).

Using the reviewed method, parameters related to the performance of the infrared detectors were calculated. The tunneling current induced by THz radiation was calculated for an asymmetric double quantum dot. The excitation couples a state which is initially localized to extended states near the continuum. The interesting fact is that the calculated current shows the same characteristics which are present in the optical spectra, such as interference effects due to the interaction between the continuum and the localized states, in addition to effects of multi-photon transitions, as already verified in the real structures recently studied. The following work was published on this topic: *Terahertz-field-induced tunneling current with nonlinear effects in a double quantum well coupled to a continuum*, Marcelo Z. Maialle, Marcos

H. Degani, Justino R. Madureira, and Paulo F. Farinas, *J. Appl. Phys.* **106**, 123703 (2009). We applied this method to quantum dots of InAs over InAlAs and covered with InP, and calculated the photocurrent. An example of the calculation with the application of an electric field can be seen in Figure 1, which shows that a photocurrent peak is expected around 100 meV, as it is seen experimentally (Figure 2).

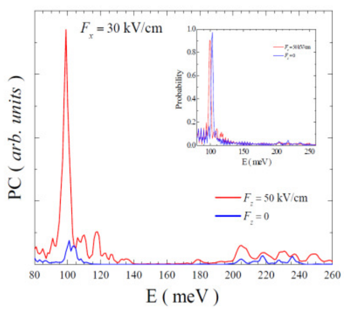

Figure 1 – Photocurrent response with and without the application of an electric field to the QDIP structure.

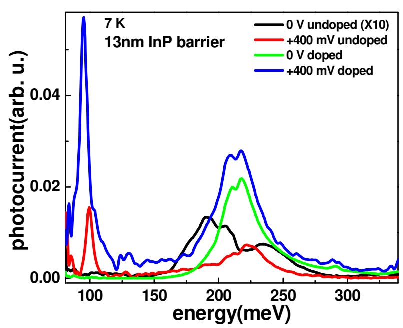

Figure 2- Photocurrent measured with and without applied electric field, in the same QDIP structure considered in the calculations.

We have the following work being prepared for publication: *Multiple-photon peak generation about the ~10 μm range in quantum-dot infrared photodetectors*, Marcos H. Degani, Marcelo Z. Maialle, Paulo F. Farinas, Nelson Studart, P. L. souza and M. P. Pires, which should be submitted to *Physical Review B* (see attachment). This work is a result of a concentrated effort by our research group to simulate, with the *split-operator* technique, the same structure studied by the experimental group, for which the results were published in P. L. Souza *et al.* (*Applied Physics Letters* **90**, 173510, 2007). The results show good agreement with the experimental data. The observed multi-photon scattering is not only in accordance with the patterns seen in the experiment but they are also necessary in order to explain the photocurrent spectra obtained in the calculations.

- ***Development of computational tools for simulation of semiconductor nanostructures***

In the period referred by this report, the LEV/IEAv team has been dedicated to the study of computational optimization of quantum well semiconductor structures.

The algorithm for self-consistent calculations of band structure of semiconductor multi-quantum well structures has been significantly improved, allowing for a convergence time one order of magnitude lower than the previous versions. It is also much more robust, allowing the calculation of structures with a large number of wells, high doping levels and thin layers. This algorithm uses a finite element method (FEM) for solving a pair of coupled differential equations: Schrodinger and Poisson equations. The potentials are calculated in an effective mass approximation. The optimum project is generated by an interactive process in which the candidate solutions are successively generated by an optimization algorithm (searching algorithm) and analyzed by a simulation algorithm (the self-consistent algorithm, in this case). In the last year, we have used, as searching algorithm, the Genetic Algorithm. Four papers related to the recent work were presented for publication: two published as extended abstracts in international congresses and two full papers accepted for publication. An additional article related to the convergence of the iterative self-consistent procedure has been prepared.

A brief description of the self-consistent simulation code and of the optimization module

The semiconductor structure we are studying is composed by several layers of different semiconductor materials, each one of the order of nanometers of thickness. These layers give rise to a series of heterojunctions in the interfaces due to the mismatch of the crystalline structure of each layer, defining a series of quantum wells and barriers. Usually, the conductivity of these semiconductor structures is increased by doping all or only selected layers.

The properties of a giving structure depends on some parameters, such as, the material and thickness of each layer, the number and sequence of layers, and the kind and concentration of doping material used in each layer.

In this period a standard GA meta heuristics was adopted. GAs are global self-adaptive algorithms that allow the solution of complex multi-modal optimization problems and do not need information from the objective function derivative. Additionally, GAs are suitable for parallel implementation in a distributed cluster of computers, as the one used at LEV.

Each design parameter is represented by a binary code and the number of bits of this code is associated to the search space of the parameter. The set of binary codes of each design parameter composes the individual, or chromosome. The individuals of the initial population are generated randomly and the following generations evolve as a function of the fitness of the individuals of the previous population by applying genetic operators on the individuals.

In order to test the optimization process, the computer program for simulation of doped nanostructures was improved. The self-consistent process adopted originally in the computer codes developed by the group was similar to the ones found in the literature. However, it was not adequate to simulate structures with several quantum wells, high doping concentrations and narrow barriers. A short description is presented below.

To take quantum effects into account we solve the time-independent Schrödinger equation:

$$-\frac{\hbar^2}{2}\nabla\left(\frac{1}{m^*(\vec{r})}\nabla\psi(\vec{r})\right)+V_T(\vec{r})\psi(\vec{r}) \;=\; E\psi(\vec{r}) \;. \tag{1}$$

Here, $\hbar$ is the Planck constant over 2π, ψ represents the wave function in the structure, m^* is the effective mass and V_T is the effective potential energy seen by one electron in the conduction band. Each layer is assumed to have a uniform composition and effective mass. It is important to point out that $V_T(\vec{r})$ is the superposition of the potential energy due to the conduction band offsets at interfaces between layers, V_0, and the potential energy that arises from the presence of ionized donors and the released free charges, V_C.

The Poisson equation is solved in order to compute the electric potential energy associated with a given charge distribution present in the multi-quantum well (MQW):

$$\nabla[\varepsilon(\vec{r})\nabla V_C(\vec{r})]=-|e|\rho(\vec{r}) \;. \tag{2}$$

where ε is the electric permittivity of the layer and e is the electron charge.

The charge distribution:

$$\rho = \rho_d + \rho_e \tag{3}$$

can be obtained from the wavefunctions, as follows:

$$\rho_e = -e \begin{cases} \dfrac{m^*}{\pi \hbar^2} \sum_{\nu} |\psi_\nu|^2 (E_F - E_\nu) & , for\ T = 0 \\ \dfrac{m^* k_B T}{\pi \hbar^2} \sum_{\nu} |\psi_\nu|^2 \ln\left(1 + e^{\frac{E_F - E_\nu}{k_B T}}\right) & , for\ T \neq 0 \end{cases} \tag{4}$$

and

$$\rho_d = \begin{cases} e \cdot n_d\ \theta(V_T - E_d - E_F) & , for\ \ T = 0 \\ e \cdot n_d \dfrac{1}{1 + 2e^{\frac{E_F + E_d - V_T}{k_B T}}} & , for\ \ T \neq 0 \end{cases} \cdot \tag{5}$$

In these equations, ρ_e and ρ_d stand for the negative (e) and the positive (d) charge densities, n_d is the doping concentration, θ is the Heaviside step function, E_d is the binding energy of the donors, E_F is the Fermi level, T is the temperature, k_B is the Boltzmann constant, and the sum spans over the discrete bound states below the Fermi level.

Therefore, we have a system of two coupled partial differential equations solved by using a weak schema (a self- consistent schema), trying to guarantee the consistency among the wavefunctions and enegy levels of the confined states and the electric charge distribution in the structure. The 1D Finite Element Method, FEM, either with first-order or second-order Lagrange-type finite elements is used to solve these equations.

The iterative process starts considering no charges present in the semiconductor structure. The Schrödinger equation (1) with only the potential energy associated to the mismatch of the crystalline structure between two layers, V_0, is solved. From the wave function ψ obtained, it is possible to compute both the Fermi energy, E_F, and the charge distribution (electrons and ionized doping atoms), assuming that the structure presents neutrality of charges. The Poisson equation (2) is solved in order to obtain the electric potential energy associated with the charge distribution. This new potential affects the charge distribution, so Eq.(1) is solved again. This iterative process continues till a given convergence criteria is achieved.

As it is well known in literature, the self-consistent process is very unstable. High changes in the electric potential energy from iteration to iteration can cause huge differences in the evaluation of the Fermi level and consequently in the charge distribution, mainly when several QW, high doping concentrations and narrow barriers are involved.

In order to achieve a more stable iterative process, a damping factor is usually applied to the solution of the Poisson equation, avoiding the huge variation of the total energy potential in the beginning of the iterative process. This way, the changes in the computed Fermi energy is dramatically reduced. However, this procedure is not enough to avoid sudden changes in the region where the electric charges are concentrated. In this condition, the procedure might not converge, particularly when symmetric structures are under consideration.

To overcome this problem, the charges are accumulated from iteration to iteration. This procedure is equivalent to the inclusion of a diffusive term in the Poisson equation which is eliminated naturally during the iterative process. However, in this approach the damping factor is adaptive, i.e., computed in each iteration. The damping factor is followed during the iterative process and it is used as a tracer. When the damping factor assumes a value equal to 1, which means no damping, for several consecutive iterations, the iterative process is assumed stable. At this point, the process is interrupted and a new iteration is carried out in order to recompute the wavefunctions and the charge distribution by using the last computed V_T. The number of iterations executed to interrupt the iterative process after reaching the point of stability is, in fact, quite conservative. The procedure adopted is very robust and the energy of the subbands and the charge distribution do not change appreciably if fewer iterations are used.

Figure 3 shows a typical convergence curve obtained in the self-consistent computation for an asymmetric MQW structure of $Al_{0.3}Ga_{0.7}As/GaAs$ with 10 wells of 7 nm, separated by barriers of 13 nm, and a larger well of 22 nm. All layers, except the right external barrier, are doped with Si (density of 9.0×10^{17} cm^{-3}).

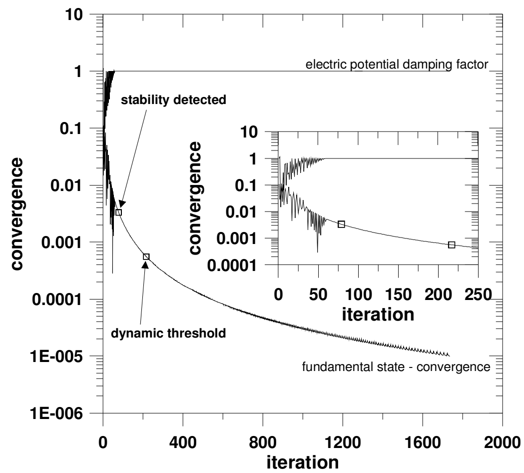

Figure 3 – A typical convergence curve obtained with the procedure adopted for self-consistent computation. The evolution of the dampin factor, the point where the stability is detected and the point where the iterative process is interrupted are also shown.

- ***Development of QDIPs on InP substrates for different operation wavelengths***

Here we briefly describe results obtained for QDIPs grown by metalorganic vapor phase epitaxy on InP substrates. Varying the sample structure we have achieved different operation wavelengths. The developed QDIP structures consist of InAs quantum dots nucleated on an $In_xGa_yAl_{1-x-y}As$ layer with different alloy concentrations and covered with InP. In order to have more operation wavelength tuning flexibility, the quantum dot structures are inserted in a quantum well. The photocurrent spectra, shown below, for the different QDIP structures which were developed demonstrate our capability of fabricating QDIPs for various operation wavelengths. For instance, for a structure such as the one depicted in figure 4a, the spectra in figure 5a with peaks around 5 and 10 microns are observed. On the other hand, for a structure such as the one shown in figure 4b, we obtain the photocurrent spectra shown in figure 5b, where peaks around 6, 8 and 12 microns are detected. This type of QDIP could detect three different wavelengths in the mid-infrared region.

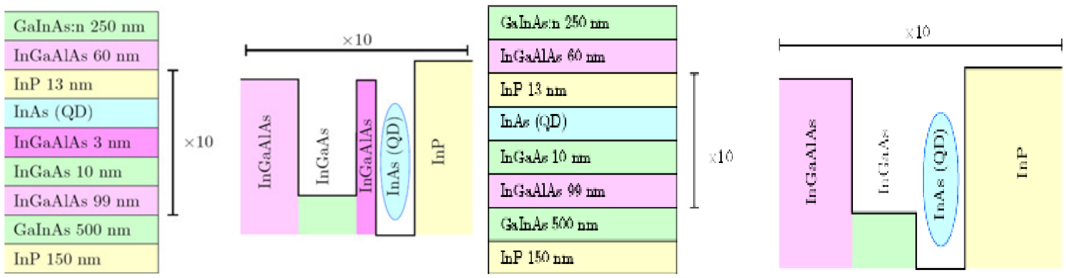

Figure 4 Scheme of QDIP structures for samples (a) 997 and (b) 990.

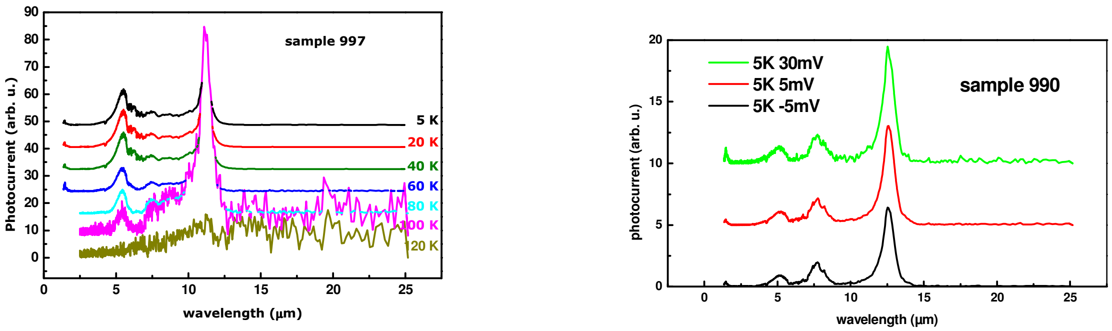

Figure 5 (a) Photocurrent as a function of temperature for another QDIP structure, showing the possibility of detecting radiation of two different wavelengths. (b) Photocurrent for a QDIP structure for three different applied bias showing the possibility of detecting radiation of three different wavelengths.

An investigation of QDIP structures as a function of doping in the quantum dots was carried out. The chosen structure was equivalent to the 997, shown in figure 4a. The corresponding photocurrent spectra are shown in figure 6. We note that the photocurrent peak at 6 microns dominates the spectra. This effect can happen depending on the measurement conditions. Depending on the applied voltage one can favor this peak or the one around 10 microns, or 120 meV.

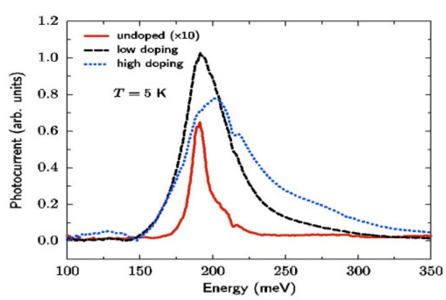

Figure 6 Photocurrent of a QDIP structure showing the change in the full width at half maximum of the peak with the doping level.

A third QDIP structure, 996, shown in figure 7, was also investigated. This structure presents a peak around 7 microns. Figure 8 shows the photocurrent for this sample and for 997. The results of the photocurrent as a function of temperature show that the device works best around 60 K and that it can work up to 100 K, implying that it can operate at liquid nitrogen.

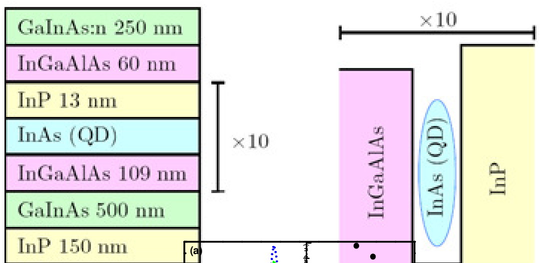

Figure 7 Scheme of sample 996

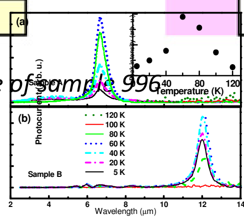

Figure 8 Photocurrent as a function of temperature for two QDIP structures (sample A is 996 and sample B is 997) showing that we can achieve operation wavelength up to 12 microns with extremely narrow peaks which can be used in applications which require high selectivity.

The results presented above demonstrate that we can fabricate QDIPs for operation in various wavelengths by slightly changing the semiconductor structure. We are in the process of optimizing these structures to reach higher operation temperatures. It should be pointed out that the interpretation of the obtained results, as the origin of the photocurrent peaks, is carried out with the help of the theoretical modeling developed, as described in the previous session of this report.

- ***Development of QWIPs for gas sensing***

With the help of simulations we have designed QWIP structures to detect infrared radiation between 3.5 and 12 microns, that is, in the MWIR and LWIR regions of the electromagnetic spectrum. These QWIPs are formed by $In_{0,53}Ga_{0,47}As/In_yGa_xAl_{1-x-y}As$ quantum wells lattice matched to InP. We have mapped all the combinations of quantum well thicknesses and alloy compositions with their corresponding detectable wavelength. This map is pictured in figure 9. With such a map in hand we can promptly choose the sample parameters required to produce a QWIP which can operate at the absorption wavelength of different gases (for instance CO_2, CO and NO).

Consulting the map, a sample to operate at 4.1 microns, radiation wavelength strongly absorbed by CO_2, was grown and the performed photocurrent measurements showed that the device could operate up to 180 K. The photocurrent spectra obtained for different CO_2 contents are shown in figure 10. As the dark current is one of the main problems to reach high operation temperatures, we have investigated different current activation mechanisms in order to understand which play a major role in the current generation for our samples. Analysing the data of dark current and photocurrent under different conditions we believe we have understood the carrier dynamics involved in the current generation and extintion in terms of optical transitions to virtual states.

A system to detect the presence of CO_2 was developed using our QWIP and a gas cell with a 10 m optical path. The system has excelent sensitivity, showing a signal degradation of 50% and 12% for CO_2 concentrations of 300 ppm for temperatures equal to 30 K and 151 K, respectively.

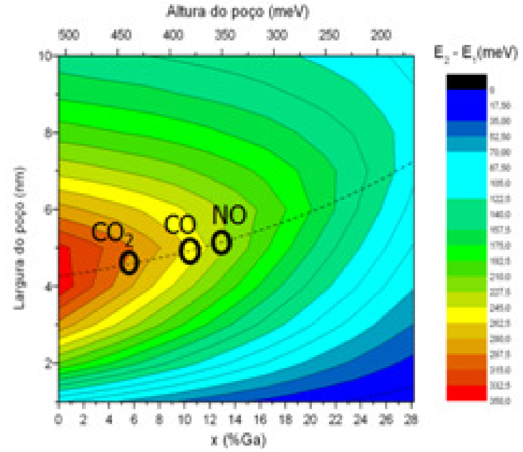

Figure 9 – Detection energy for different quantum well thicknesses and alloy compositions.

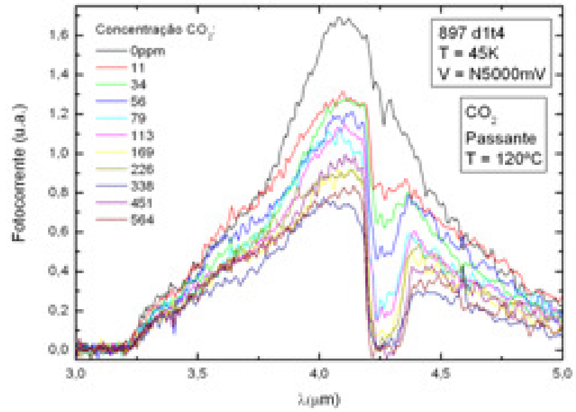

Figure 10 – Photocurrent of the QWIP for different CO_2 concentrations.

- ***Development of GaAs-based QDIPs***

Here will be described the progress realized with the MBE (molecular beam epitaxy) growth, process and tests of GaAs-based QDIPs at the University of São Paulo. Initially, we started with a very simple sample structure in order to be able to check each stage of the growth. The main idea during this first year was to establish a standard procedure for the growth and processing the devices, as well as to build different types of experimental setups in order to test their performance. The samples were grown on top of semi-insulating GaAs substrates and consisted of an active region, containing 10 Si-doped layers of InAs quantum dots separated from each other by 40 nm of GaAs, surrounded by two 1μm-thick Si-doped GaAs layers on top of which the electrical contacts were deposited (figure 11).

Initially, we tried to process the samples at the Center for Semiconductor Components (CCS), of the University of Campinas, which had all the equipments required for our devices. However, some of them frequently showed technical problems that made impossible to develop reproducible procedures and recipes. We then were obliged to process the samples in 3 different labs because none of them had all the equipments needed. These were the Laboratory of Integrated Systems (LSI) and the Laboratory of Microelectronics (LME) of the Engineering School at USP, and the Laboratory of Microfabrication of the National Laboratory of Synchrotron Radiation (LNLS). Photolithography was used to define the physical size of the detectors with mechanical masks designed in our lab. 2mm x 2mm mesas were made by wet chemical etching and 0.5mm x 0.5mm Ni/Ge/Au contacts were deposited by electron-beam evaporation and annealed at 420 °C during 30s. Thin Cu wires where then soldered on these electrical pads using small In balls.

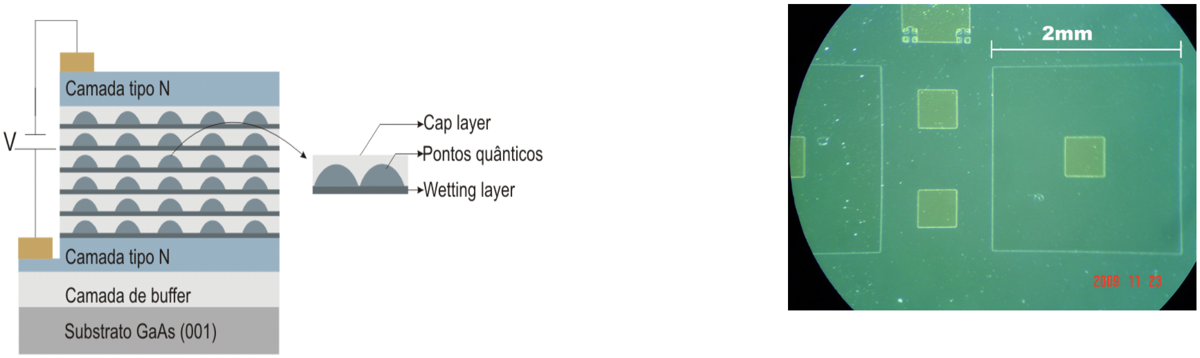

Figure 11: *(Left) General QDIP structure, showing the active region (with 10 QDs layers) surrounded by two Si-doped layers that will receive the electrical contacts. (Right) Processed QDIP (after photolithography, wet etching and metal deposition), showing a 2mm x 2mm mesa with 0.5mm x 0.5mm top and bottom Ni/Ge/Au contacts.*

In order to test the devices, we build from scratch several experimental setups able to check their optical and electrical properties. That was possible due to several grants coming from state and federal funding foundation, as well as from the present Institute.

High-sensitivity I-V curves were performed in a new optical cryostat operating with liquid nitrogen and equipped with ZnSe windows that are transparent in the 0.5 – 19 μm range. A temperature controller allowed measurements between 77 and 300 K, and a very sensitive source-meter was able to detect currents below fA level. All these equipments were connected to a computer and controlled by a software running under Labview (figure 12). Low-noise triaxial cables using a guard system were used in order to minimize triboelectric noise, leakage currents and capacitance. Dark-current measurements could be carried out with a dark (and cold) shield surrounding the sample.

Figure 12: *(Left) Full I-V curve system with 77 – 300 K capability. From left to right, we can see the monitor showing some windows of the control software, the optical cryostat, the source meter (above) and the temperature controller (below). (Right) Main menus of the control software running under Labview.*

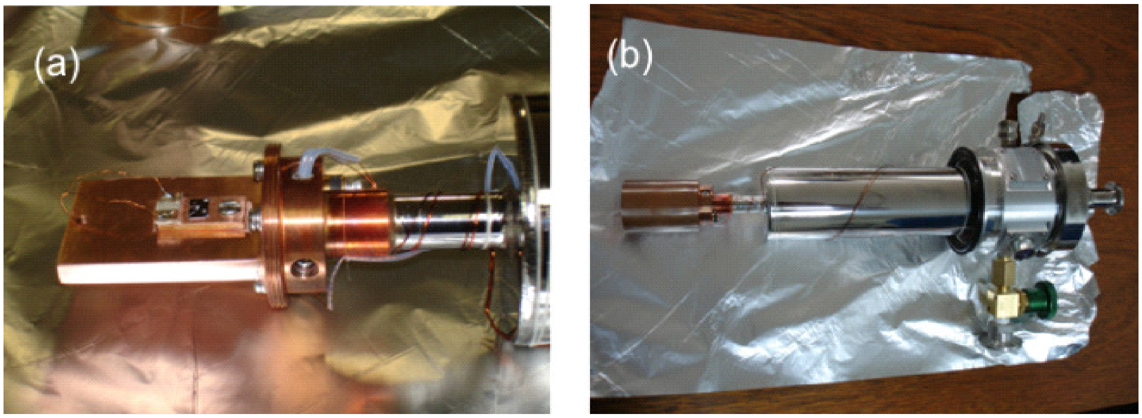

Figure 13*: a) Sample fixed on the cold finger of the optical cryostat. b) Dark shield screwed around the sample in order to perform dark-current measurements. The dark shield and cold finger are in thermal contact with the liquid-nitrogen dewar that can be seen on the right.*

Noise measurements of the photocurrent and dark current were also implemented and totally automatized under Labview, using a dynamical spectrum analyzer able to compute the fast Fourier transform of the electrical signal in real time. Responsivity measurements using a blackbody and lock-in techniques were also implemented and are now being automatized under Labview. Finally, a commercial FTIR operating in the mid infrared system was bought in order to determine the absorption spectrum of the devices. We are now building a special sample holder that will fit in the FTIR system in order to allow measurements with 45° incidence using a waveguide geometry (with multiple reflections) able to detect the signal coming from QWIPs (that do not respond to normal incidence) and to enhance the weak signal coming from QDIPs (due to their intrinsic low quantum efficiency).

After processing the samples and building the experimental setups, we tested some devices to check the consistency of the growth, process and measurement procedures. As will be shown, the devices show quite a large dark current. This is normal because, at the moment, our basic QDIP structure contains only InAs QDs layers and GaAs barriers. In the next structures, we will insert some thin AlGaAs barriers that should decrease the dark current by several orders of magnitude.

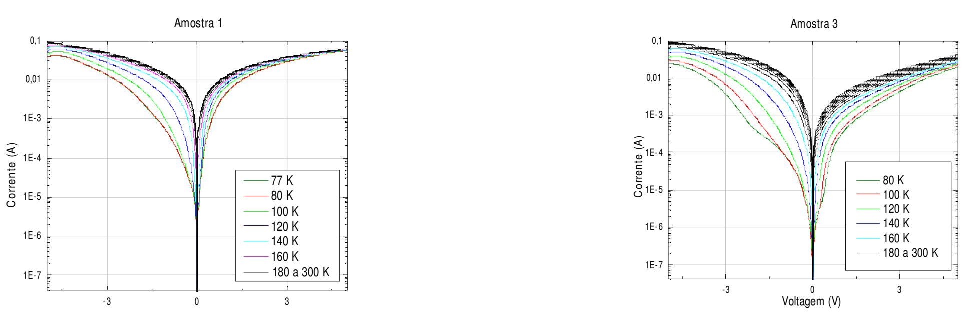

Figure 14*: I×V curves performed with the dark shield as a function of temperature for 2 QDIPs having a different Si doping of the contact layers: (left) 10^{18} cm^{-3}; (right) 5×10^{17} cm^{-3} .*

Figure 15 shows preliminary responsivity curves of the same 2 QDIPs. Since the signal is not yet calibrated, these curves are actually the photocurrent curves obtained when the devices are submitted to the radiation of a blackbody heated at 800K. Since we can observe a response to the infrared radiation coming from the blackbody as a function of the bias voltage, we can conclude that our devices indeed behave as photodetectors. However, we will only be able to know the spectral response of the devices once the new sample holder for the FTIR measurements will be ready. Figure 15 also shows the photocurrent noise as a function of the bias voltage for the same 2 QDIPs. The noise current was measured at 1kHz, far from the 1/f noise.

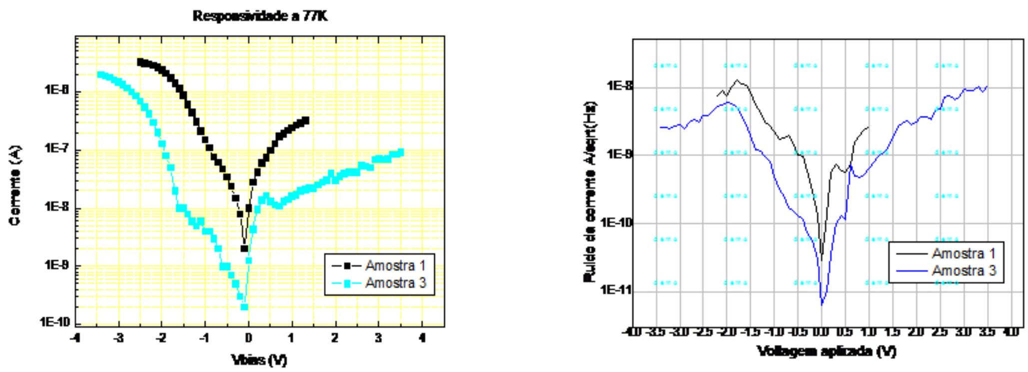

Figure 15*: (esquerda) Responsivity curves (photocurrent) as a function of applied voltage for two QDIPs with different doping levels of the contact layers: (black) 10^{18} cm^{-3}; (blue) 5×10^{17} cm^{-3} . (right) Photocurrent noise measurements as a function of applied bias for the same two QDIPs.*

We are now finishing the automatization of the responsivity setup and the sample holder for the FTIR measurements that will soon be used to complete the set of experimental data needed to fully characterize the devices. Therefore, we hope that very soon, we will be able to grow, process and test almost any type of infrared photodetector.

In parallel to these experimental activities, we are also developing some computational methods to predict the energy levels of the quantum wells and dots used in our devices, as well as trying to simulate some of the properties of our devices (photocurrent, dark current, responsivity). Initially, these calculations were performed with the software Mathematica, but the calculation time became very long in some cases due to the complexity of the problem. We are now rewriting most of the routines in C language that is much faster. We hope that, very soon, we will be able to use these calculations to design novels structures with better performance. To get more realistic results, we intend to include other relevant effects such as strain, segregation and doping of the layers.

- ***Responsivity measurements of infrared sensors***

For the development of photodetectors, responsivity measurements are essential. A verification of the consistency of the responsitivity measurement methods used was done. The spectral responsivity was measured by two different approaches: one measuring the relative responsivity using an FTIR, measuring the integral responsivity using a cavity black body and finding the spectral responsviity by deconvolution. The other approach is to measure the spectrum of one infrared lamp as coming out of a monochromator, using a calibrated sensor, and find the spectral responsivity by comparison. Although the second approach may be easily affected by alignment, a reasonable accord between the two approaches was found. It should be noted that the second approach cannot be applied to a sensor with weak response, due to the low power density coming out of the monochromator. The detector used was InGaAs/InAlAs quantum well infrared photodetector, grown on an InP substrate. The details of this work are in the master dissertation of Kenya Aparecida Alves. The goal of the experiment was to check the reliability of the characterization apparatus.

- ***Assemblage and integration of photodetectors***

In 2009 the following activities have been done as regards the assemblage and integration of photodetectors:

- numerical platform for combined simulation of photodetectors and electronic circuits;
- circuit topologies for voltage-mode photodetector read-out;
- circuit topologies for current-mode photodetector read-out;
- feasibility study of optical transistors in adaptive optical systems.

Numerical platform for combined simulation

We have incorporated to SPICE (Simulation Program with Integrated Circuit Emphasis) spectrum libraries, as well as parameters and dimensions of semiconductor optoelectronic devices in order to calculate current densities, quantum efficiency, resistivity and resistances in biased junction detectors or in photoconductors. The platform has been fed with known Si parameters and the simulation results have been compared to known results. This platform allows one to combine carrier transport models in optoelectronic devices with the circuit functionality offered by SPICE. This solution can be used to aid in the identification of the most adequate circuit topology for a given photodetector.

Signal-to-voltage conversion

The circuit topologies investigated for the signal-to-voltage conversion were: CAPS (Complementary Active Pixel Sensing) e CTIA (Capacitive Transimpedance Amplification).

CAPS

Compared to the traditional active-pixel detection (APS), the CAPS topology reduces the impact of the supply voltage reduction as CMOS feature size decreases. However, this methodology demands a larger area for the pixel circuitry, which is not limiting in the case of infrared sensors as their light-sensitive regions will be fabricated on a suplementary substrate. As in the conventional APS pixel, the internal capacitance bias results in a non-linear behavior of the output signal which can be minimized by employing short integration intervals. The advantage of this topology lies in the increase of the output-signal range. The schematics of the investigated circuit is shown in Figure 16.

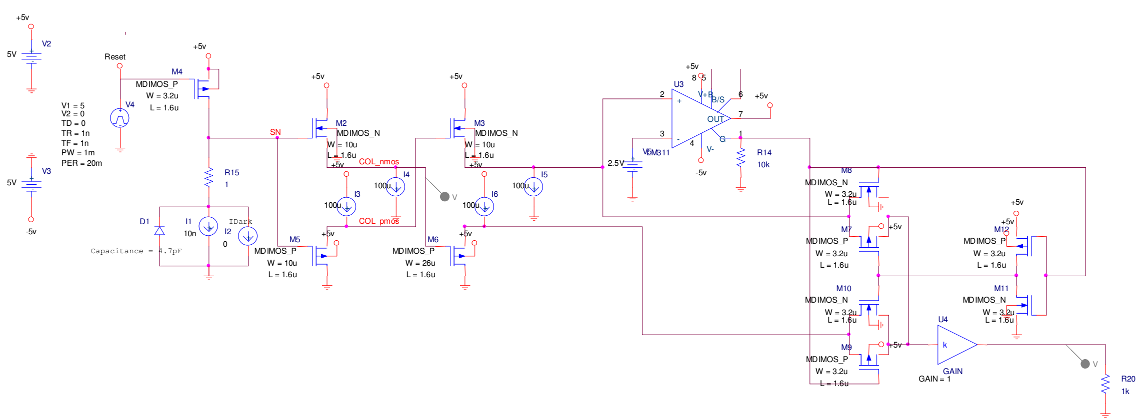

Figure 16. CAPS schematic circuit.

The pixel is reset by transistor M4 allowing full reset up to Vdd. The photodiode capacitance stores a fixed charge that depends on the reset voltage and on the junction capacitance. The photogenerated current acts towards discharging the internal capacitance as soon as M4 is turned off. The voltage across the capacitor drops as a result of charge integration. M2 works as a source-follower 'buffer' and reproduces the voltage across the photodetector at the output signal line. M2 introduces a V_{th} (threshold) drop as well as a V_{DS_sat} (source-drain saturation voltage). Integrating the complementary PMOS transistor at the source follower, the output voltage might reach a value close to Vdd. There is still a second stage with M3 and M6 for gain adjustment, which is essential for the linearity of the output signal. A comparator monitors the output signal and alternates the real output between NMOS and PMOS through digital switches. The output signal to the PMOS and NMOS are shown in Figure 17.

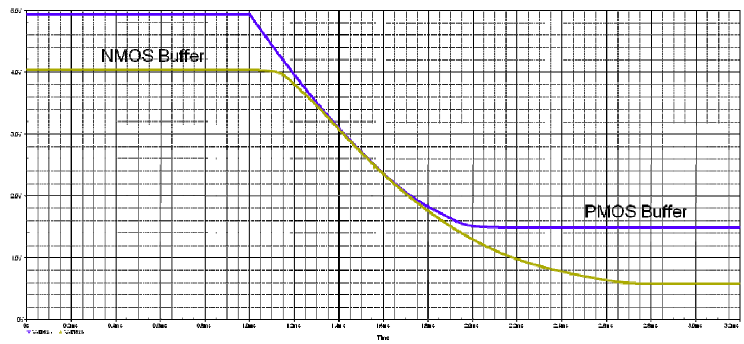

Figure 17. Separate NMOS and PMOS outputs as a function of integration time.

The combined signal after the comparator is shown in Figure 18, illustrating the enhancement of the output voltage swing.

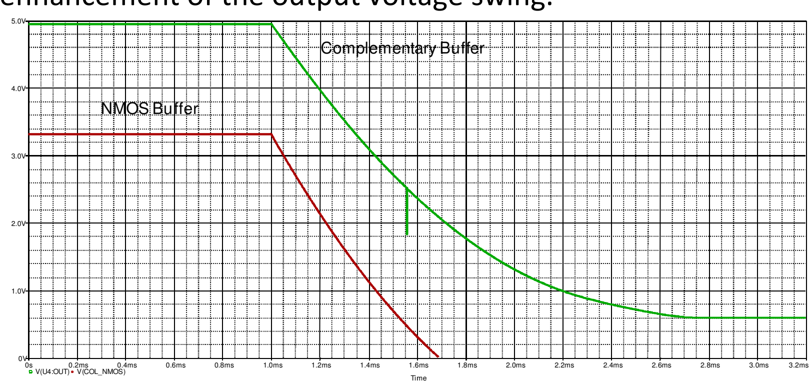

Figure 18. Comparison of the CAPS output signal with that of a conventional APS with NMOS.

CTIA

A Capacitive Transimpedance Amplifier is composed of an operational amplifier, a reset transistor and a capacitor. The CTIA uses an external capacitor for charge integration, so the intrinsic photodiode capacitance has almost no effect on circuit performance. Speed can also be improved with this approach, as the integrating capacitor can be chosen for a determined goal. Almost no biasing effect is shown in the integrating capacitor, as it is a parallel plate capacitor, which does not have depletion-region variation issues.

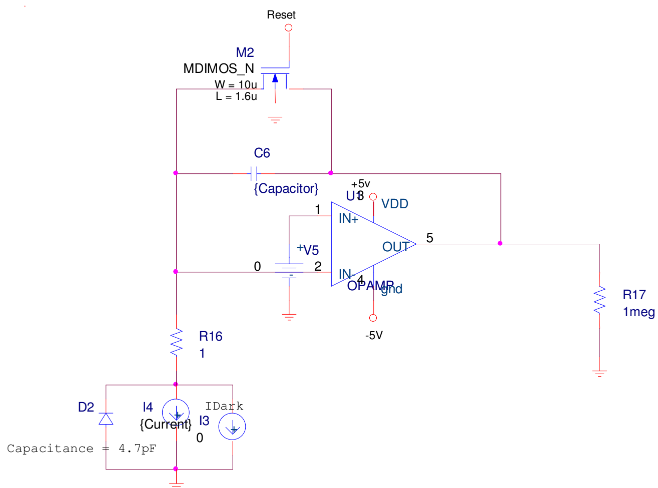

Figure 19. CTIA circuit schematics.

The amplifier is first reset by turning the Reset transistor ON. When Reset is switched OFF, the charge integration period starts. The OPAMP works as a signal integrator. The current source and parasitic parallel resistance of photodiode (R_{sh}) can be modeled by its Thévenin equivalent circuit as a voltage source in series with a resistance ($R_{The} = R_{sh}$). The integrator output after the reset pulse is given by:

$$Vout = \frac{-1}{R_{the} * C_{int}} \int Vth * dt$$

considering the negative signal of V_{The} (Thévenin equivalent voltage = $I_{ph}*R_{sh}$, where I_{ph} is the photocurrent) and assuming it to be constant due to a constant illumination, the output is a growing ramp, which slope is defined by R_{The} and C_{int} (C_{int} = C6). The output signal is shown in Figure 20.

The circuit was simulated with a 1pF integrating capacitor. The photocurrent was swept from 10nA to 100nA with 10nA linear steps. We can see from Fig. 8 that the output is very linear with respect to the photo-generated current. The following circuit stages are the same as that one of an APS: CDS, sample & hold, Analog to Digital Converters. Another simulation was performed. It shows the change in the slope of the output signal, if the capacitor is increased from 1pF to 10pF in 1pF linear steps. The results are presented in Fig. 21. The photocurrent was fixed in 10nA.

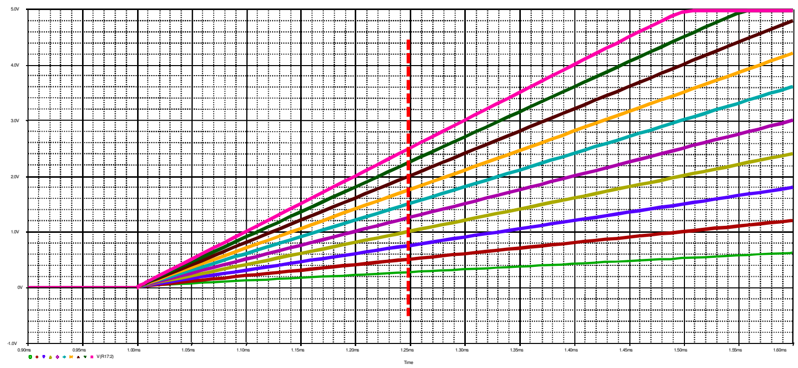

Figure 20. Output due to various photo-generated currents (10nA to 100nA in 10nA linear steps)

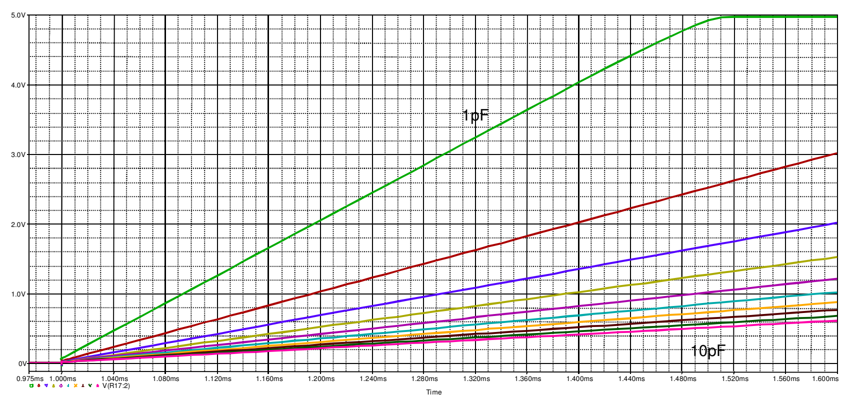

Figure 21. Output slope variation due to change in integrating capacitor value (1pF to 10pF in 1pF linear steps)

CTIA was successfully simulated in the absence of noise and reset switch non-idealities. A second circuit that employs a bipolar transistor as the switching element and a commercial general purpose opamp was also designed. Its schematic is presented in Figure 22.

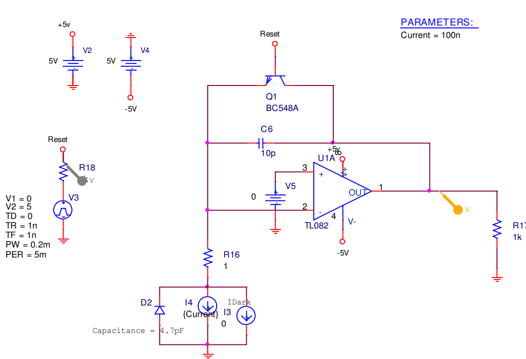

Figure 22. CTIA with bipolar reset switch.

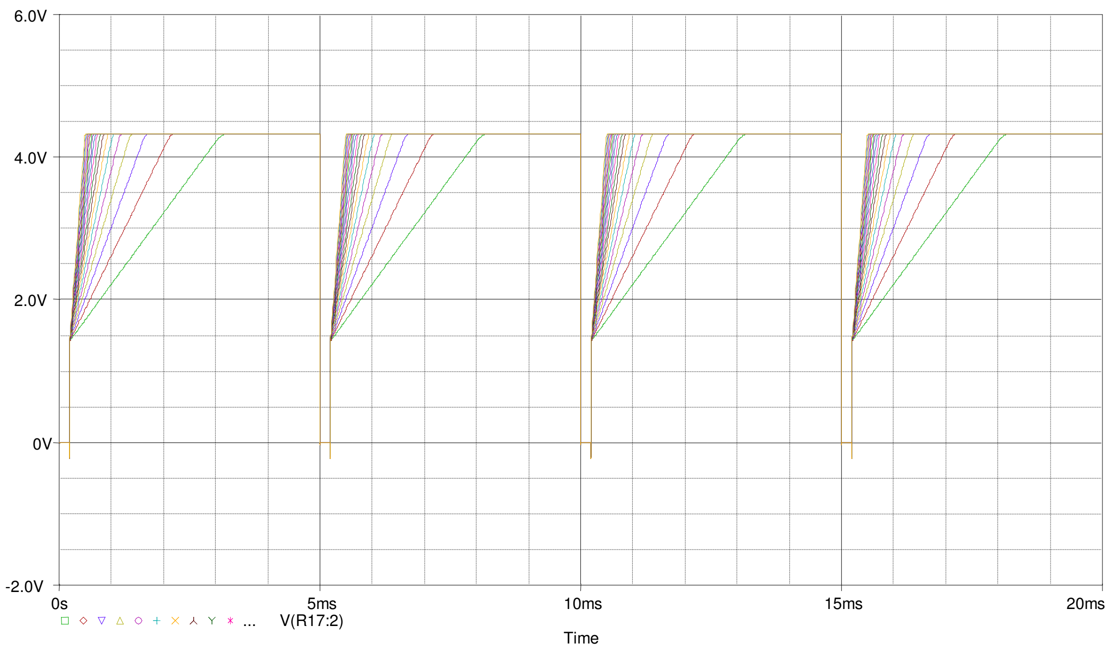

Figura 23. CTIA output with bipolar reset switch.

We can see that a constant offset appears in the output signal due to the introduction of a bipolar transistor as the reset element. A working prototype was also implemented to test the concept. Opamp – TL072 and BC548 as the reset switch. Figure 24 shows the output waveform for a single output where an offset can be observed.

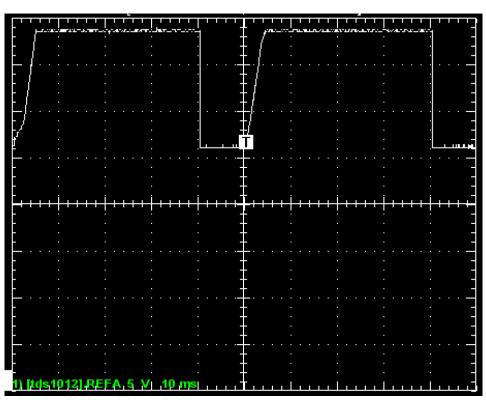

Figure 24 Signal CTIA output with bipolar reset switch.

To try to overcome this problem, a third approach was proposed. Now, a commercially available CMOS analog switch (CD4066) will be employed as the reset switch. Simulation shows that the offset problem was minimized, as seen in Figure 25.

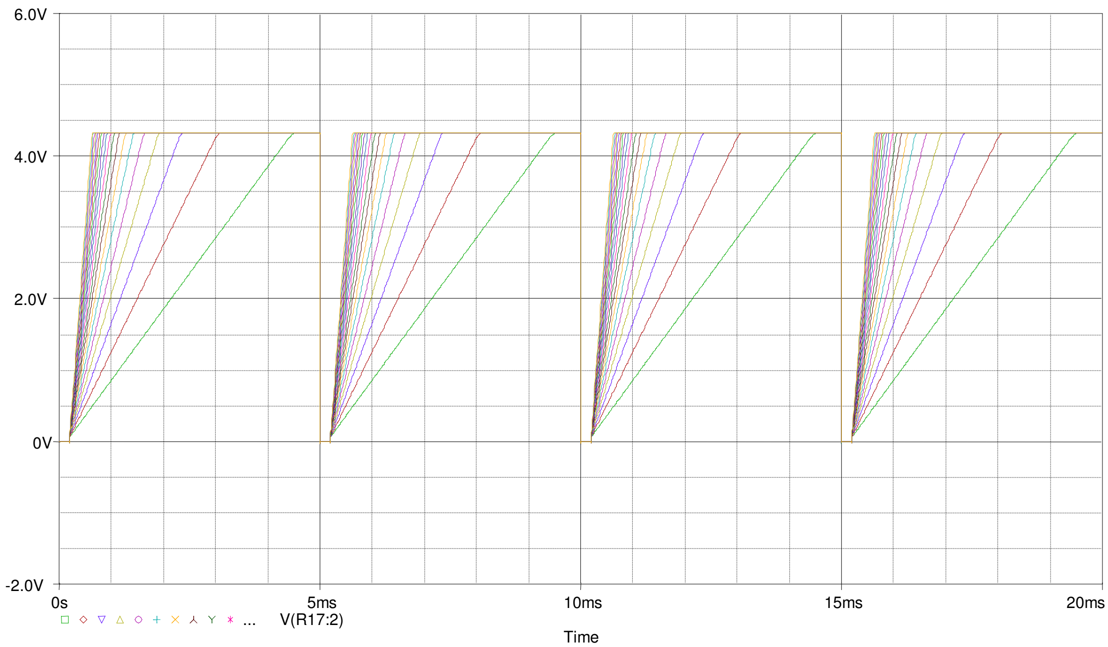

Figure 25. CTIA output with CD4066 reset switch

Signal-to-current conversion

Signal-to-current conversion presents a couple of advantages in comparison to the signal-to-voltage approach:

- fixed voltage at the data line allowing larger bandwidths;

- analog arithmetic operation in smaller chip areas than those required by equivalent digital operations on voltage mode;

- pixel signal swing does not decrease as the CMOS feature size decreases;

Some disadvantages, however, are:

- circuits more prone to noise;

- signal transistor results in non-linear output;

- higher fixed pattern noise (FPN) in case of 1D and 2D photodetector arrays;

- higher power dissipation.

From various possible topologies we decided to investigate the one that employs corrent mirrors as proposed by Huang [Huang, Y., Current Mode CMOS Image Sensor, PHD Thesis, 2002]. The double amplification presented on this approach leads to high sensitivity, allowing the read out of very low currents. The pixel works on current-mode, however, the output current is converted into an analog voltage and subsequently into a digtal signal by an ADC. A number of analog operations can be realized before the current-to-voltage conversion. This topology is highly sensitive to the aspect ration of the used FETs, in such a way that if each photodetector has its own readout circuit, this may result in an image suffering from a substantial amount of FPN noise. This type of noise can however be greatly reduced by software or firmware in an image post-processing step.

The current-mode pixel is presented in Figure 26. There is a current mirror composed of M1 and M3; transistors M2 and M4 operate as a current conveyor. Current output from M5 controls the gate voltage of M2, or the drain voltage of of M1. M4 then acts as a current buffer and conveys current from the high conductance source to the low conductance drain, where the pixel output is connected.

When row select signal is low, M7 is on and pixel current is output to the column bus. When row is not selected (row signal is high), M6 allows current discharge. Transistors M1 and M2 are the main sources of FPN noise. The relationship between their aspect ratio defines the internal gain of each pixel. Another noise source is the output switch, M7. Because of charge injection, current spikes can be observed on pixel output. Dummy transistors should be included to avoid this effect.

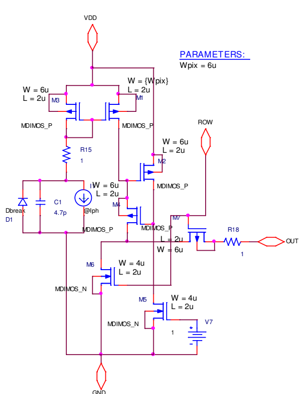

Figure 26 – Schematics of the current-mode pixel circuit.

Four pixels were assembled on a column and connected to a column bus. Each pixel has a different photogenerated current and will be read at a different time, defined by the Row Select control signal. The circuit that generates the signal is presented in Figure 27. A counter controls the outputs of a demultiplexer, which is connected to all the pixels on the column, enabling each pixel sequentially.

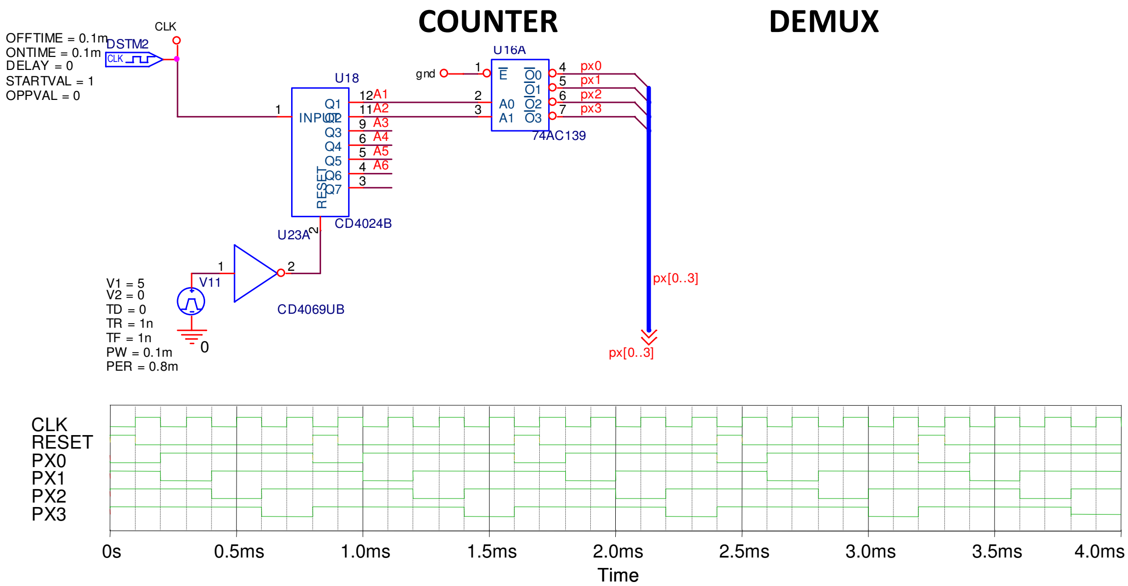

Figure 27 – Circuit for addressing pixels on an array and control-signal scheme.

The multiplexation scheme and connection of the common secondary current mirror on the data bus is presented in Figure 28. The primary current mirror is inherent to each pixel and is incorporated into the pixel box symbol.

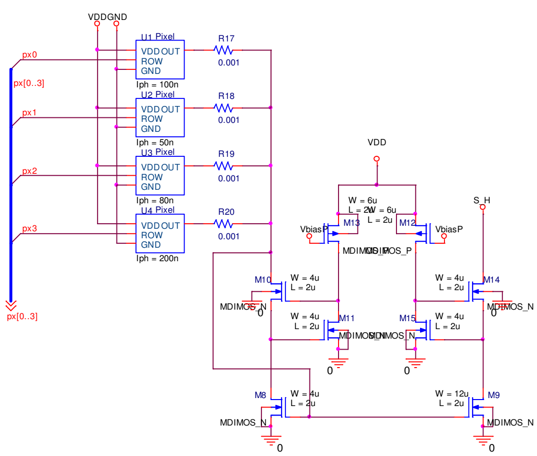

Figure 28 – Secondary current-mirror on a 4-pixel column bus.

The complete circuit that follows the data bus is shown in Figure 29 together with the resulting output signal. This circuit encompasses current-to-voltage conversion and signal amplificiation by means of a voltage follower amplifier.

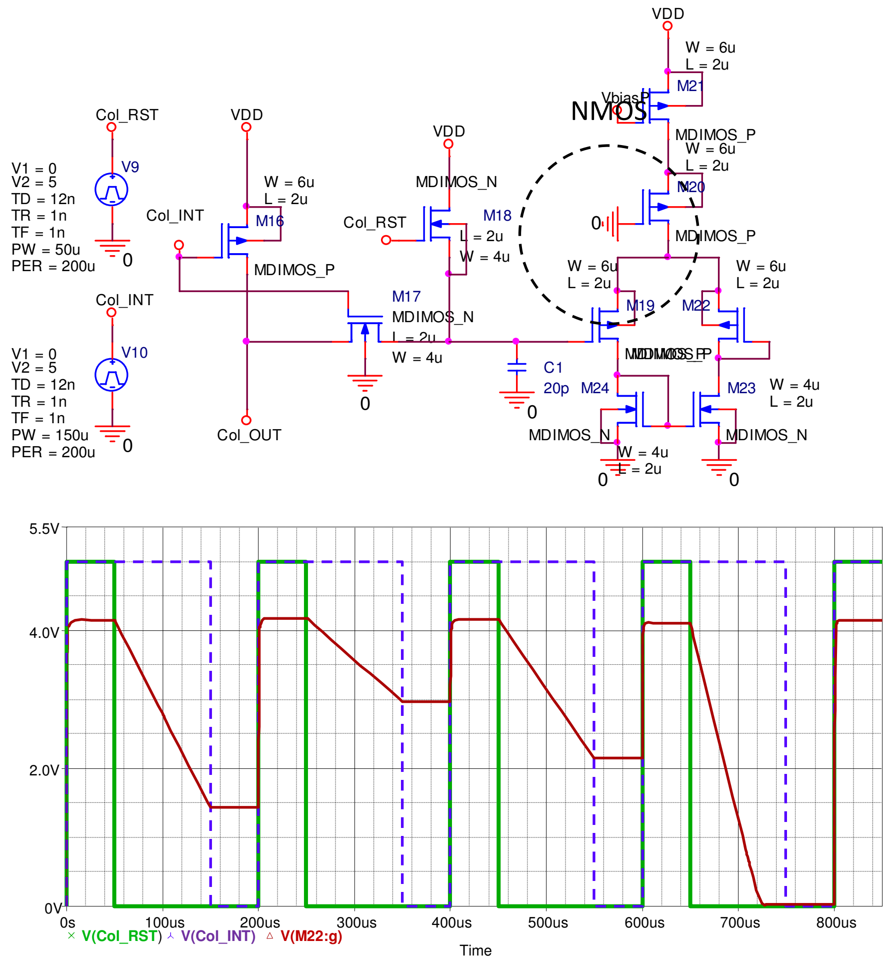

Figure 29 – Output circuit connected to the data bus and output signal at various circuit stages.

Optical transistor as an element of an adaptive optical system

The UFAM group investigates the optical properties of semiconductor microcavities in GaAs 100Å quantum wells with $A_{0.3}Ga_{0.7}As$ barriers between DBR (AlAs/A $_{0.2}Ga_{0.8}As$) mirrors. It has been observed that the output signal of these structures has a strong dependence on the input laser-beam angle, which originally suggested a disadvantage to the device. However, from interaction with the OptMA/DEE/UFMG team, there was an idea to investigate these structures for the detection of wavefront profiles, eliminating a great deal of image or data processing in the wavefront reconstruction process in adaptive optical systems. Currently, we are evaluating the accuracy and repeatability of the output signal for the laser-beam.

2) Investigation of fundamental properties in quantum structures for infrared detectors

In this line of research, three topics were investigated: a) structures with quantum dots coupled to a parabolic quantum well; b) charge extraction mechanisms from quantum dot structures; and c) implementation of an experimental setup to measure photocurrent with a monochromatic source.

- ***Quantum dots coupled to parabolic quantum wells***

To increase the possibility of control of the tuning of the absorption energy of quantum dot photodetectors, in this work we propose a new kind of heterostructure, which consists of quantum dots inserted in a parabolic quantum well. The InAs quantum dots were grown inside parabolic quantum wells, obtained by a continuous variation of the composition of the quaternary material $In_{0.53}Ga_xAl_yAs$. The alloy composition changes quasi-continuously between $In_{0.53}Ga_{0.47}As$ (x = 0.47 e y = 0) and $In_{0.53}Ga_{0.27}Al_{0.20}As$, always lattice matched with InP, in a way that a parabolic potential energy profile is obtained (Figure 30). We control the total thickness of the parabolic wells in order to change the energy levels of the dot-well system, thus tuning the optical transitions between bound states.

After processing of the devices, measurements of photoluminescence, dark current and photocurrent response were performed at several temperatures. The photoluminescence measurements indicate that the material grown is of excellent quality, demonstrating the degree of precision that can be obtained by the *metalorganic vapor phase epitaxy* technique. This is an important result, since, after these samples, new structures with different conduction band profiles will be proposed and grown, to try to increase the selectivity of the detectors. The observation of photocurrent with normal incidence shows that a quantum dot state is really involved in the transitions. Since the optical transition is different for samples with different well thicknesses, it is confirmed that the absorption is not between states strongly confined in the quantum dot but should be between a deep quantum dot state and a final state which is localized in the dot-well structure.

As the main results of the study of these samples, we mention the fact that they work well up to temperatures above 180 K, which is higher than the temperatures obtained in the structures described in the first research line of this report, and the possibility to change the width of its spectral response as a function of the applied bias (Figure 31). For negative bias the detector displays a relatively sharp bandwidth while for negative bias the photocurrent response is much broader.

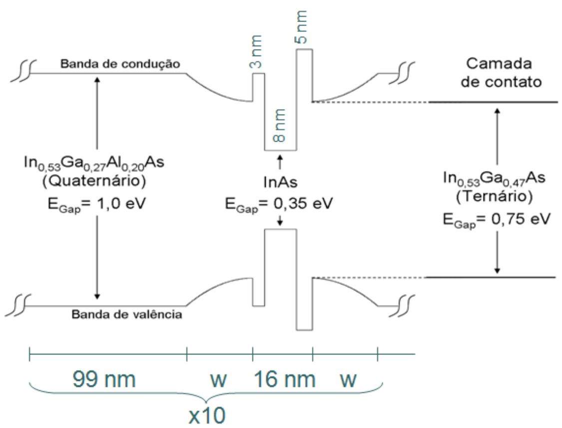

Figure 30 – Conduction band profile of the sample

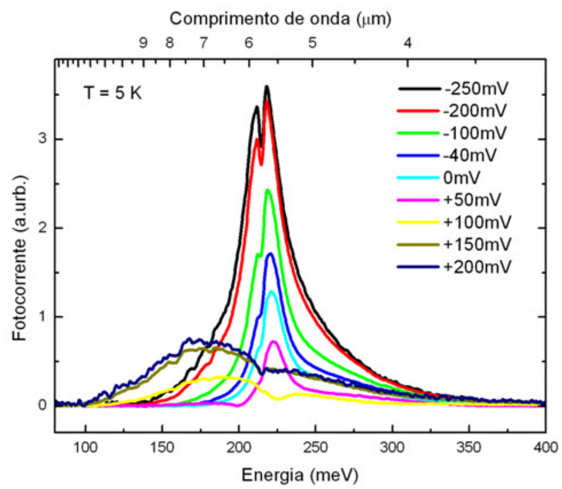

Figure 31 – Photocurrent response as a function of applied bias

- ***Charge extraction mechanisms from quantum dot structures***

The mechanisms of charge carrier extraction in self-assembled quantum dot infrared photodetectors were investigated with measurements of the photocurrent response, dark current and current-voltage characteristics in several samples: quantum dot multi-layers, quantum dots inserted in a parabolic quantum well and quantum dots with coupled quantum wells. The full understanding of extraction and collection of the photoexcited electrons can guide in the proposal of photodetector structures with high signal to noise ratio. We investigated two structures in more detail: the first one has as active region a layer of self-assembled quantum dots of InAs inserted between thin barriers of InAlAs, followed by a InGaAs quantum well between InAlAs barriers. The second sample has as active region a layer of InAs self-assembled quantum dots inserted in a quantum well of parabolic profile, made with a variable concentration InGaAlAs alloy. The parabolic well is surrounded by asymmetric potential barriers, InP in one side and InGaAlAs on the other side. For the first structure, two narrow and intense photocurrent peaks, one at 190 meV and a second one at 230 meV, are seen for both positive and negative applied bias voltages. Here, positive bias means that the electric field points from the substrate to the top of the structure. Close to zero bias, photocurrent in both directions is observed, negative current around 190 meV and positive current around 230 meV (Figure 31). For the second structure, the photocurrent response shows a relatively sharp peak centered at 240 meV for positive bias. For negative biases a much broader peak around 180 meV, which is already present at positive bias, grows rapidly in intensity and dominates the spectrum for the highest bias values (Figure 32). Again, around zero bias the dual behavior, with photocurrent in two opposite directions, is observed. Full three dimensional numerical calculations of the energy levels and transition oscillator strengths were performed in the envelope function approximation for both structures, in order to identify the transitions. The reverse current observed at low bias is attributed to the asymmetries in the structures. A paper which reports these results is being written.

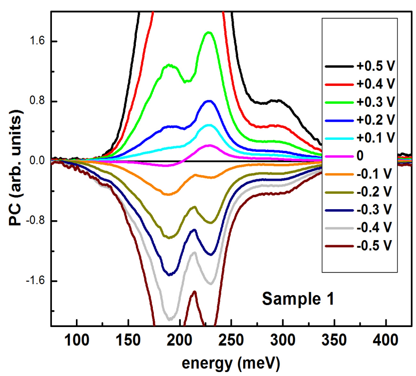

Figura 31

Figure 31 – Photocurrent of a QDIP structure with quantum dots coupled to a lateral quantum well.

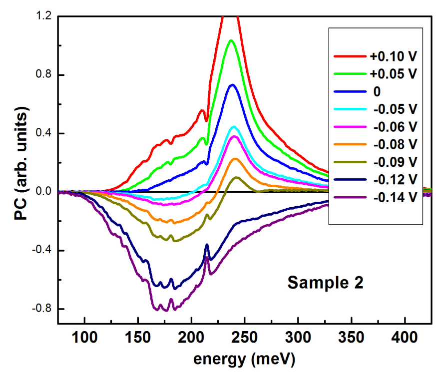

Figura 32

Figure 32 – Photocurrent of a QDIP structure with quantum dots inserted in a parabolic quantum well.

- ***Setup for photocurrent measurements with a monochromatic source***

Photocurrent measurements are necessary to analyze the electrical response (current) of a photodetector structure as a function of the incident light. Usually, what is desired is the photocurrent spectra, that is, the current which is obtained for each wavelength (or energy) of the light that the detector sees. To obtain the spectra several methods are used, amongst them the more common are the method with a monochromatic source and the FTIR (*Fourier Transform Infrared Spectroscopy*) method.

An experimental setup for photocurrent measurements with a monochromatic source was realized and is operational at the DISSE headquarters, in PUC-Rio. In the measurement with the monochromator, the light which is emitted by a lamp (which is chosen accordingly to the range of the spectra of interest) goes through a diffraction grating before being directed to the sample. In the light path, several optical components (mirrors, lenses, filters) are used to guide and control the beam. The signal from the sample is collected and transferred to a computer, which displays the desired spectrum. The experimental setup implemented for these measurements is shown in Figure 33.

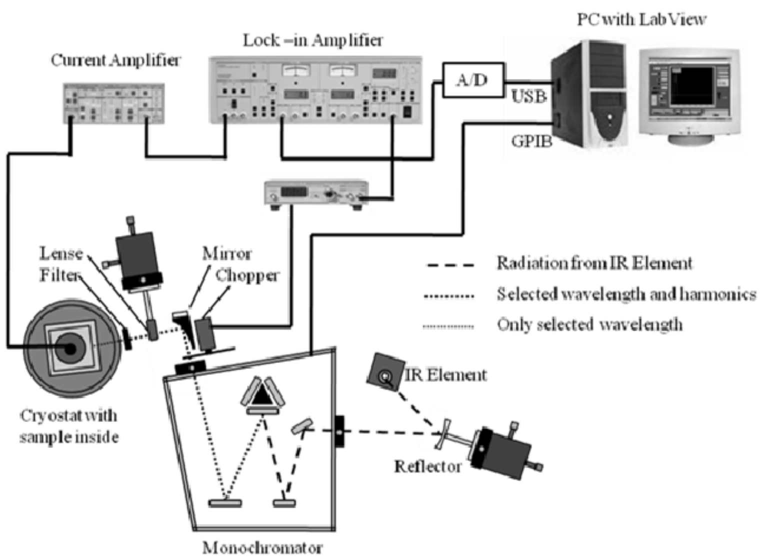

Figure 33 Setup for photocurrent measurements with a monochromator

In measurements with an *FTIR* spectrometer the light that the sample sees is not monochromatic. Instead, it goes through a Michelson interferometer and is modulated in time. To obtain the desired spectra, the electrical signal generated by the sample in response to the infrared radiation undergoes a Fourier transform. Figure 34 shows the experimental setup which is used for this measurement. In the mid-infrared range (wavelength between 2 and 20 microns) the infrared sources are very weak and the detectors not so sensitive; therefore the experimental setup is delicate. For this reason the FTIR setup is used preferentially in this range. However, since in the FTIR measurement the photodetector sees several wavelengths at the same time, it is more difficult to separate the different mechanisms of photocurrent generation. This is the reason for the implementation of the photocurrent measurement setup with a monochromatic source. We expect that the comparison of the results of the two spectroscopic techniques will help in the understanding of the physical phenomena which play a part in the performance of the QDIP structures.

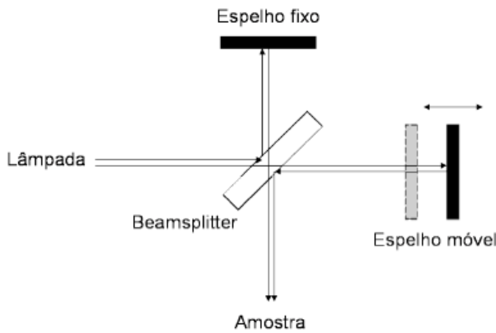

Figure 34 Experimental setup for measurement of the photocurrent with the FTIR spectrometer.

Figure 35 shows photocurrent measurements made with the two techniques. It can be seen that the main result is essentially the same. In fact, one should expect differences in the two spectra only when the photocurrent measured by the FTIR technique is affected by the presence of photons with different wavelengths. The results we have obtained so far show that the setup is operational and can be used to investigate different physical phenomena in the QDIPs.

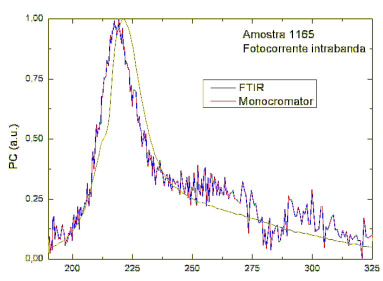

Figure 35 – Comparison of photocurrent response measurements from the FTIR and monochromator techniques.

- ***Memory effect in multi-quantum well structures for QWIPs***

In a joint work between the groups from DF-UFMG, PUC-Rio, IF-UFRJ and IEAv, an investigation was made of the electronic transport in multi-quantum well structures of the type that is used for quantum well infrared photodetectors (QWIPs). From magnetotunneling measurements, a *memory* effect in the magnetic field was found in such structures, in the sense that the vertical electric resistivity of the samples after application of an intense magnetic field is different from the resistivity before the application of the field. In this investigation, the electric field domain configuration in multi-quantum well structures and its changes with magnetic field were also studied and explained. The results were published in the paper "Current bistability in a weakly coupled multi-quantum well structure: a magnetic field induced 'memory effect'", Journal of Physics D: Applied Physics, vol. 42, p. 145109, (2009).

3) Growth of self-assembled quantum dots

- ***Epitaxial growth of self-assembled quantum dots***

In this activity different quantum dot structures were grown on InP and GaAs substrates by MOVPE and MBE. The results of the growth of these samples are included in the first part of the report on the scientific results above.

- ***Consolidation of the centre for epitaxial growth of semiconductors***

With respect to this topic, semiconductor samples were grown and distributed to members of DISSE for our research. Additionally, we have supplied samples to the groups of Professor Newton Frateschi from the INCT on Photonics and Optical Communication and Professor Rodrigo Prioli from the INCT-NAMITEC, as mentioned earlier in this report.

The most important step in this topic is the purchase of the new MOVPE equipment and the construction of the building to house it. With additional funds from FINEP, the equipment was fully especified and 60% of the total value has already been paid.

In order to install this equipment at PUC-Rio, the headquarters of DISSE, the architectural, structural and installations projects are underway and the construction is planned to start in May. The MOVPE reactor should be delivered in November.

- ***Site-control of the nucleation of quantum dots on pre-patterned substrates***

There is great interest in controlling the nucleation position of self-assembled quantum dots on a semiconductor crystal. In the nucleation of quantum dots in the Stranski-Krastanow growth mode the dots are randomly distributed over the growth plane causing problems for the fabrication of certain devices. For instance, to optimize the exciton-photonic mode coupling in a photonic crystal the quantum dots must be at a maximum of the electric field of the photonic mode to which it should couple. Our research on site-control of the nucleation of quantum dots followed two approaches: introduction of nanoidentations using atomic force microscopy and nanolithography by anodic oxidation.

With respect to the introduction of nanoidentations using an atomic force microscope the investigation was carried out in collaboration with Professor Rodrigo Prioli from INCT-NAMITEC. The nanoidentation technique was improved reaching the short term goal. We have also better understood the quantum dots formation mechanisms on nanolithographed substrates and the role of the introduced dislocations was revealed. Two articles were published with these results:

1)Nanoscale dislocation patterning by scratching in na atomic force microscope e Growth of linearly ordered arrays of InAs nanocrystals on scratched InP. In the investigation reported in this article the atomic force microscope was used to scratch the InP surface along specific crystalographic directions. Transmission electron microscopy was used to analyze the nature of the resulting plastic deformations. Scratches along the <110> direction mainly show screw dislocations introduced by a coherent rotation of two planes generating a butterfly-like pattern. Scratches along the <100> direction show dislocations close to the surface, possibly due to the interlocking between the dislocations and the friccional heating in tne region close to the surface. The nature of the structural defects suggest that the velocity of the dislocations is much lower than that of the probe during the scratching procedure.

2)Growth of linearly ordered arrays of InAs nanocrystals on scratched InP. In this article we have shown that it is possible to control the nucleation sites of InAs quantum dots grown by MOVPE on an InP surface pre-patterned by using a diamond tip coupled to an atomic force microscope to produce scratches along specific crystal directions on the substrate surface. Matrices of InAs nanocrystals were produced along the <100> and <110> directions on a pre-patterned InP substrate. The growth of quantum dots depend on the crystal directions of the scratches. Due to the nucleation of structural dislocations highly localized along the lines, small crystals linearly oriented along the scratches on the <001> direction were obtained.

The group leader from UNIFAP, Amapá, Professor Henrique Fonseca Filho, is now in the process of installing the atomic force microscope, which was bought with the INCT-DISSE funds, so that he can continue this topic of research at UNIFAP.

Several techniques have been proposed to control the growth position of self-assembled quantum dots, in an effort to improve the coupling of the dots with the photonic modes. The method of Anodic Oxidation Nanolithography (AON) that we are developing has the advantage of allowing the location of the dots *before* the growth, and not *a posteriori*, in addition of being of very easy application. During this period we made a significant progress in our aim of obtaining InAs and InGaAs quantum dots on InP and GaAs substrates in pre-determined positions. In this technique, a chosen design is patterned in micrometric scale on the substrate surface by oxidation, in an environment with controlled humidity, by the application of a potential difference between the substrate and the probe, in an atomic force microscope (AFM). The oxide that is formed is then removed in an acid solution. The nano-metric holes that are left on the surface act as nucleation points for the subsequent growth of the self-assembled quantum dots. Another option that we are also exploring is to use the nano-metric hole matrix made in the InP substrate as a mold for the deposition of an InGaAs layer, lattice matched with the InP. The amount of InGaAs deposited is just enough to cover the holes, plus a very thin epitaxial layer over the plane. After that, the InGaAs is covered with an InP layer. This way of producing quantum dots is very attractive, since, as the InGaAs is lattice matched with the substrate, there are no tensions in the quantum dot region and the optical quality of the structures is better than the self-assembled ones. The disadvantage is that, due to the limitations of the AON process, the quantum dots that are obtained normally have lateral dimensions bigger than the ones grown by the Stranski-Krastanow method. Nevertheless, the dimensions that we have been obtained, diameters of the order of 100 nm and heights between 2 and 4 nm, are enough to achieve quantum confinement and optical transitions in the range of operation of our photonic crystals. Figure 36 shows the oxide pattern in a InP sur-face and, on the side, the same pattern after oxide removal. The quality of the depressions that are left on the surface is excellent. However, we do not have complete control yet of the growth of self-assembled quantum dots using these depressions as nucleation points. They do work effectively as nucleation sites but not all and some quantum dots grow out of the pre-determined positions. We are now changing the parameters of the process (relative humidity of the environment, applied voltage, oxidation time) in order to achieve control of the shape of the depressions, since their efficiency as nucleation points should change with shape and size.

We have achieved better results with InGaAs quantum dots grown lattice matched on InP. Figure 37 shows an AFM image and height profiles obtained before and after the growth of a thin layer of InGaAs on an InP substrate patterned by the AON technique. The depressions, with approximately 150 nm of diameter and 4 nm of height, are nearly totally filled with the InGaAs. Other samples were made covering the InGaAs layer with a 200 nm thick layer of InP, to confine the charge carriers. These samples are now being studied with micro-photoluminescence measurements. The results obtained so far are described in more detail in the Master of Science thesis of Carlos G. Pankiewicz (UFMG 2009). These results were also presented at the 14th Brazilian Workshop on Semiconductors Physics - BWSP-14, Curitiba, 23-27 March 2009.

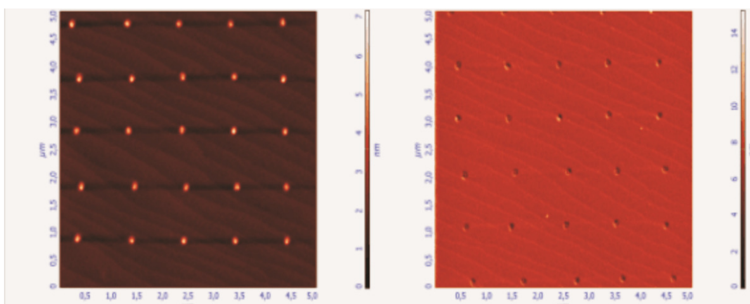

Figure 36 – Atomic force microscopy images of oxide dots (left) and the resulting pattern of depressions produced after the oxide is removed (right), on an InP surface.

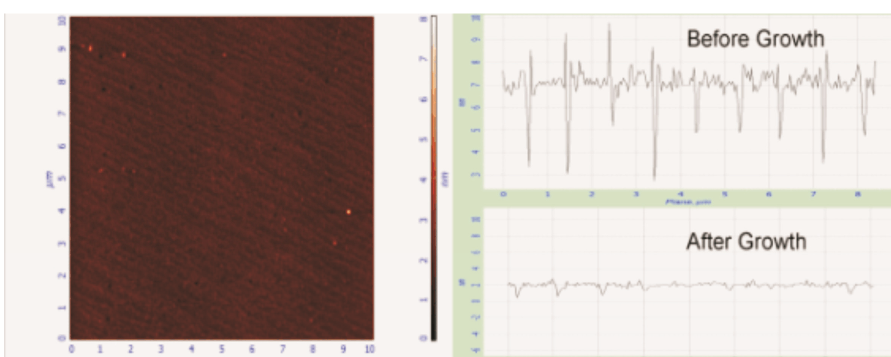

Figure 37 – The figure in the right is an image of atomic force microscopy of a InGaAs surface lattice matched with the InP substrate. The good quality of the surface demonstrates the quality of the growth. The diagrams in the left are height profiles obtained also by AFM before and after the InGaAs growth. The depressions are clearly seen before the InGaAs deposition. The profile obtained after growth shows that these depressions are nearly totally filled with InGaAs deposition.

- ***Computational intelligence techniques applied to epitaxial growth***

During this period an extension of the use of neural networks in predicting the growth of self-organized quantum dots was carried out. We investigated the ability of the neural network to predict the density and height dispersion of quantum dots for a given growth condition (growth temperature and pressure, gas flow, deposition time and buffer material). The experiments were performed using filed growth data of samples with a single layer of self-organized quantum dots. The results are very satisfactory. The average errors obtained for the prediction of density and dispersion are, respectively, 21.4% and 16.13%. Those results are very suitable for the amount of data on samples available for the research. Figures 38 and 39 below explain graphically the performance of neural network for two cases. The blue curve represents the experimental results and the red curve the result predicted by the neural network in the three main stages of the technique (training, validation and test). One may notice that the neural network is sometimes not able to reach the exact experimental data, but it can follow the trend, which is already a great advance in the growth of self-organized quantum dots.

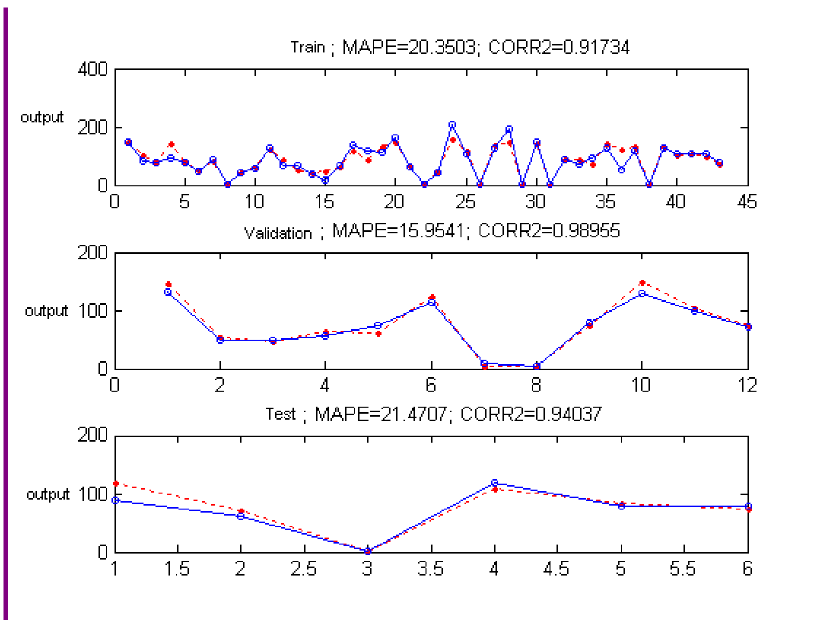

Figure 38 - Comparison of the prediction by neural networks for the density of quantum dots

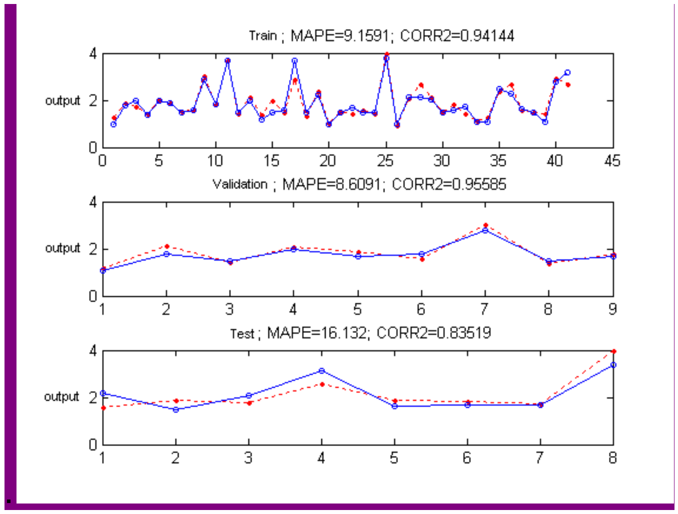

Figure 39 - Comparison of the prediction by neural networks for the dispersion of the height of quantum dots

4) Novel physical phenomena on semiconductor quantum dots for novel devices

- ***Quantum electrodynamics effects in a microcavity***

We setup the optical pump&probe measurement system on this first year of INCT-DISSE. We have used a Ti:Saphire pulsed laser (Trestle 50 model from DelMar Photonics), whose pulse is split in two parts with a controlled femtosecond resolution delay between them. The emission is coupled to a high resolution spectrometer (Jobin Yvon T64000), as illustrated in Figure 40. This system complements our previous measurement set-up, i.e. now we have an optical high resolution system both in time and in energy.

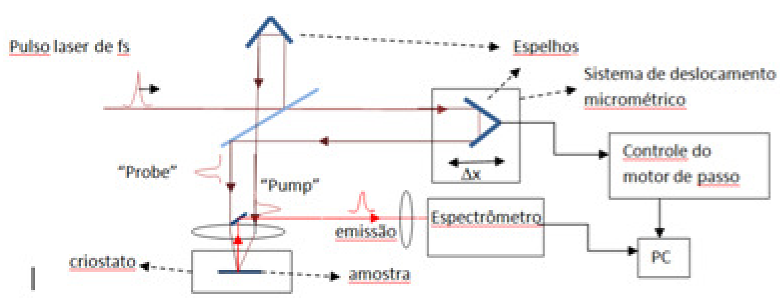

Figure 40 Experimental setup for pump & probe system, using a Ti:Saphire laser pumped by a solid state CW laser.

Now, a master student Thonimar Alencar is working on that system. He is investigating the Faraday rotation effect in a microcavity in a resonant excitation process, where polaritons with polarization (spin) correlated to the input pump pulse are generated. The spins are rotated by the Faraday effect by 180 degree, before being scattered by the second probe pulse into the cavity mode. The delay between the first scattered polaritons and the second probe is measured in time and energy. The rotation time can be measured as a function of cavity detuning, i.e. we can observe the rotation time for a polariton with photon-like behavior or as exciton-like, just by moving the laser spot around the sample. In Figure 41 we see the polariton scattering in the pump & probe experiment as a function of pump power intensity.

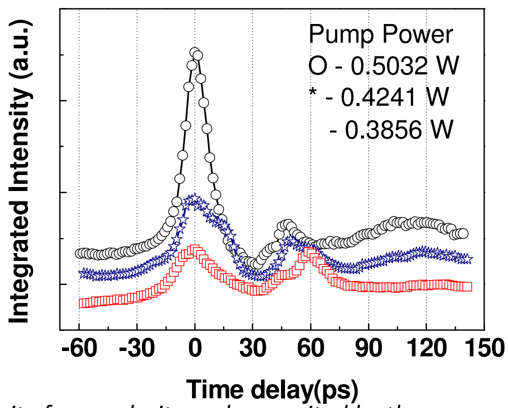

Figure 41: Emission intensity from polariton when excited by the pump and probe pulses as a function of delay and power intensity.

- ***Quantum electrodynamics studies in photonic crystals – Fano interference***

Reflectivity measurements were performed in photonic crystals with L3 cavities, such as the one shown in Figure 42. We made measurements in the crossed polarization configuration, in a micro-photoluminescence setup. A peak in the reflectivity, linked to the fundamental photonic mode, was observed. This technique opens the way to investigate the confined electromagnetic mode structure in photonic crystal cavities even at high temperatures, since it does not depend on the efficiency of buried photon emitters, such as embedded quantum dots. Changing the polarization of the incoming light, we observed that the reflectivity lineshape changes considerably, as shown in Figure 43.

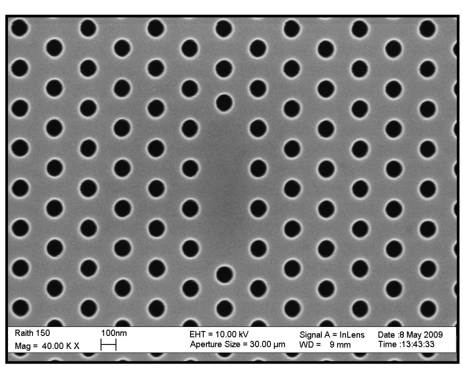

Figure 42 – Two dimensional photonic crystal, with a periodic triangular pattern of air holes in GaAs. The defect consists in the absence of three holes in line, the so-called L3 cavity.

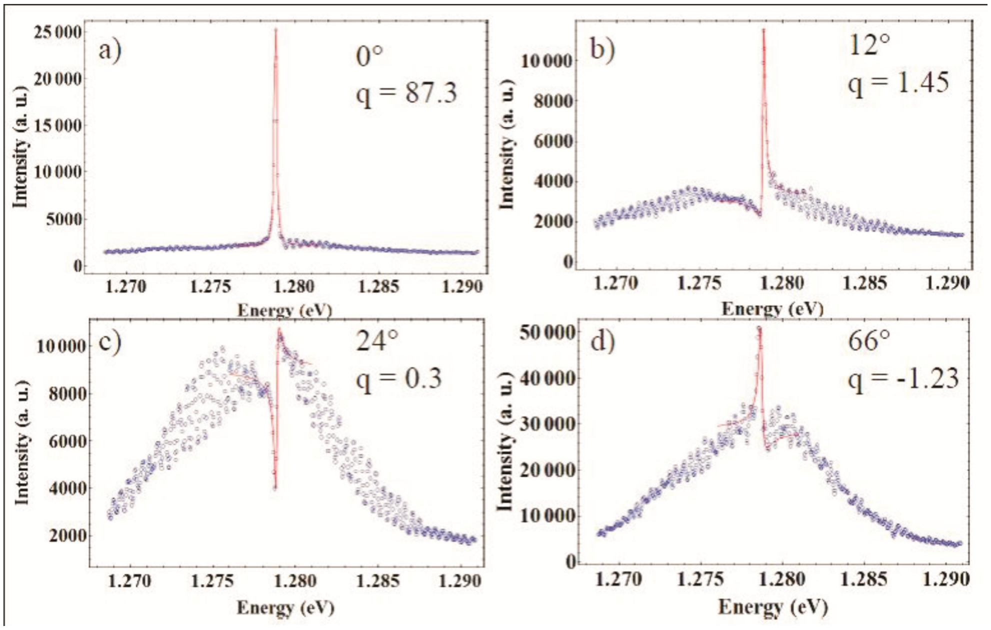

Figure 43 – Reflectivity spectra of a photonic crystal with a L3 cavity, for different polarization angles of the incoming light. The dots represent the experimental data and the red lines are fits considering a Fano interference between the photonic mode and the reflectivity continuous. The Fano parameter q, shown for each spectra, is the only adjustable parameter.

- ***Optical Transistor based in semiconductor microcavities***

Some calculations were performed which allowed us to design new samples with the highest cavity quality factor, generating an increase of the lifetime, of the spontaneous emission factor while further reducing the laser threshold of confined polaritons. The inclusion of multiple quantum wells (QW's) enables a significant increase of the Rabi energy, associated with the binding energy of polariton. This increase should allow finding polaritons at high temperatures. The nonlinearities that allow the development of an optical transistor will be stronger with the replacement of QW's for InGaAs quantum dots (QD's). This implies a shift of the cavity of about 800 nm to 1000 nm, which can influence the efficiency of the laser emission. The next step is to implement these structures with the interaction with the laboratory of epitaxial growth of USP, Prof. Alain Quivy, member of DISSE.

Our research showed the minimum conditions that the cavity must have for the formation of polaritons. The cavity formed by two mirrors DBR (Distributed Bragg Reflector) of $AlAs/Al_{0.2}Ga_{0.8}As$ must have a minimum reflectivity of 88%. This result was obtained analyzing the shift of upper and lower polariton branches in the strong coupling regime.

Our main interest is to get polaritons at high temperatures, where the thermal energy should not be higher than the Rabi energy that characterizes these states. Thus, to obtain a Rabi-Splitting of about 30 meV (since the thermal energy at 300K is equivalent to ~ 26meV), our results indicate that it would take at least 5 QW's positioned at anti-nodes of the normal mode of the cavity.

The use of materials that can enhance the oscillator strength of confined excitons is limited by the use of arsenics due to limitations of MBE growth. Thus, the use of quantum dots (QD) of InGaAs can increase the confinement of the exciton, leading to a high oscillator strength (about 12 times higher than in GaAs QW's).

V. National and International Events: work presentations, seminaries and talks; round tables; publications

a) Invited Seminars and Talks

1) **Workshop do Centro de Nanociência e Nanotecnologia da UFRGS**
Patrícia Lustoza de Souza invited to give a talk in the workshop in August 2009 in Porto Alegre for graduate students of Rio Grande do Sul. Title: *Fabrication of sel-organized nanostructures and its application on semiconductor devices..*
2) **Summer School on Fundamentals and Materials for Novel Sensors**
Patrícia Lustoza de Souza gave a course for graduate students from the entire country. The school was co-organized by The TU-Braunschweig and DISSE and took place in July 2009 at PUC-Rio. Title: *Infrared photodetectors based on semiconductor nanostructures.*
3) **Self-assembled quantum dot infrared photodetectors: Theory and Experiment**
Invited by Professor Klaus Enslin, group leader on Nanophysics at ETH-Zurique, Nelson Studart gavethe above cited talk where the main theoretical results were discussed and compared with the experimental ones obtained by the members of DISSE. October 2009.
4) **Research Seminar at INPE**
Marcelo Maialle presented the following talk *Multi-photonic processes in QDIPs* in 23/02/2010.
5) **Semiconductor Nanodevices**
Invited talk by Patrícia Lustoza de Souza at in Campinas in March 2009.
6) **Federal University of Juiz de Fora**
Paulo Sérgio Soares Guimarães was invited for a seminar for researchers, graduate and undergraduate students on Physics and Engineering. The seminar was part of the Knowledge Week of that University. Title: *Photonic crystals and quantum dots: controlling the light in semiconductor materials*, 22/10/2009.

b) International conferences

1) **Very narrow band quantum dot infrared photodetector for 12 μm**
T. Gebhard, P. L. Souza, D. Alvarenga, C. A. Parra-Murillo, P. S. S. Guimarães,
K. Unterrainer, M. P. Pires, G. S. Vieira, J. M. Villas-Boas, M. Z. Maialle, M. H. Degani, P. F. Farinas, N. Studart.
Intraband Transitions in Quantum Wells Conference, Montreal, Canada, September 2009.

2) **InGaAs/InGaAlAs/InAs/InP very selective quantum dot infrared photodetector for 12 μm**
T. Gebhard, P. L. Souza, D. Alvarenga, C. A. Parra-Murillo, P. S. S. Guimarães,
K. Unterrainer, M. P. Pires, G. S. Vieira, J. M. Villas-Boas, M. Z. Maialle, M. H. Degani, P. F. Farinas, N. Studart.
22nd Annual Meeting of the IEEE Photonics Society, Belek Antalya, Turkey, October de 2009.
3) **Dual behavior quantum dot infrared photodetectors**
D. Alvarenga, T. Gebhard, C. Parra-Murilo, P. L. Souza, P. S. S. Guimarães, K. Unterrainer, M. P. Pires, G. S. Vieira and J. M. Villas-Boas
16th International Conference on Electron Dynamics in Semiconductors, Optoelectronics and Nanostructures, Montpellier, France, August 2009.
4) **Superposition of positive and negative contributions to the photocurrent spectrum of InAs/InGaAlAs/InP quantum dot infrared photodetectors**
T. Gebhard, K. Unterrainer, P. L. Souza, M. P. Pires, D. Alvarenga and P. S. S. Guimarães
16th International Conference on Electron Dynamics in Semiconductors, Optoelectronics and Nanostructures, Montpellier, France, August 2009.
5) **Modeling of the growth of quantum dots by neural network**
O. P. Vilela Neto, A. Singulani, M. A. C. Pacheco, M. B. R. Vellasco, M. P. Pires and P. L. Souza
International Conference on Advanced Materials, Rio de Janeiro, Brazil, September 2009.
6) **Growth if InMnAs nanostructures over InP patterned substrates using MOVPE**
M. P. Pires, R. Kawabata, G. Penello, H. Fonseca Filho, E. Sinnecker, P. L. Souza, B. Neves e R. Prioli
13th European Workshop on Metalorganic Vapor Phase Epitaxy, Ulm, Germany, June 2009.
7) **Polariton laser dynamics on a GaAs SQW microcavity**
Thonimar Vieira de Alencar Souza, Victor Shmidt Comitti, Marina Bezerra Eiras da Silva, Franklin Massami Matinaga, 11th International Conference on Optics of Exciton in Confined Systems (OECS' 11), Set/2009, Madrid , Spain.
8) **A self-consistent analysis of subband alignment in a superlattice with one larger well.**
Angelo Passaro, Roberto Yuji Tanaka, Ademar Muraro Jr, Gustavo Soares Vieira, Nancy Mieko Abe
14th International Symposium on Applied Electromagnetics and Mechanics, ISEM´09, September 20-24, 2009, Xi'an, China.

c) National Conferences

1) **Probing carrier dynamics in quantum dot structures in the mid-infrared region by using two complementary spectroscopy techniques**
S. Dornstauder, R. Kawabata, P. L. Souza, G. Penello, M. P. Pires, T. Gebhard, K. Unterrainer, D. Alvarenga, P. S. S. Guimarães andJ. Smoliner
14th Brazilan Workshop on the Physics of Semiconductors, Curitiba, March 2009.
2) **Growth of magnetic semiconductor using MOVPE**
R. Kawabata, P. L. Souza, G. Penello, M. P. Pires, E. Sinnecker, H. Fonseca Filho and R. Prioli
14th Brazilan Workshop on the Physics of Semiconductors, Curitiba, March de 2009.
3) **Quantum dot infrared photodetectors including a quantum well parabolic potential**
G. Penello, M. P. Pires, D. Alvarenga, T. Gebhard, K. Unterrainer, R. Kawabata, P. L. Souza, P. S. S. Guimarães, G. S. Vieira, J. M. Villas Boas and N. Studart
14th Brazilan Workshop on the Physics of Semiconductors, Curitiba, March 2009.
4) **Computational Inteligence Optimization Method for AlGaAs/GaAs Quantum Well Solar Cells**
A. Singulani, P. L. Souza, O. P. Villela Neto , M. P. Pires e M. C. Pacheco
Proceedings of the 24th Symposium on Microelectronic Technology and Devices (SBMicro 2009), Natal, September 2009. ECS Transactions 23, 515-520 (2009).
5) **Superposition of Positive and Negative Contributions to the Photocurrent Spectrum of InAs/InAlGaAs/InP Quantum Dot Infrared Photodetectors**
T. Gebhard, D. Alvarenga, M. P. Pires, K. Unterrainer, P. S. S. Guimarães and P. L. Souza
Proceedings of the 24th Symposium on Microelectronic Technology and Devices (SBMicro 2009), Natal, September 2009. ECS Transactions 23, 521-526 (2009).

6) **Desenvolvimento de um transistor óptico intrínseco usando microcavidades semicondutoras.**
E. A. Cotta.
XXVII Encontro Nacional de Físicos do Norte e Nordeste, Belem, November 2009.

7) **Cd-S Decorated Multi-Walled Carbon Nanotubes as a Material for New Devices**
Marcos Flávio O. Silva, Wagner N. Rodrigues, Douglas R. Miquita, Luiz O. Ladeira, and Carlos B. Pinheiro
Proceedings of the 24th Symposium on Microelectronic Technology and Devices (SBMicro 2009), Natal, Rio Grande do Norte, from August 31 to September 3, 2009. ECS Transactions 23, 121-125 (2009).

8) **Pipelined Successive Approximation Conversion (PSAC) with Error Correction for a CMOS Ophthalmic Sensor**
F. SILL, D. W. de LIMA MONTEIRO
Symposium on Integrated Circuits and Systems Design - SBCCI, 2009, Natal - RN. Proceedings of the 22nd SBCCI, 2009. v. 1. p. 239-243.

9) **Fabrication and Characterization of Active Pixel Sensors (APS) Using Simple Metal Gate nMOS Technology**
A.S.O. Furtado, J.A. DINIZ, D. W. de LIMA MONTEIRO
Symposium on Microelectronics Technology and Devices - SBMicro, 2009, Natal - RN. Proceedings of SBMicro 2009 - ECS. Pennington - New Jersey - EUA : The Electrochemical Society Transactions, 2009. v. 23. p. 461-467

10) **Intrinsically Self-Amplified CMOS Image Sensor**
P. M. Santos, D. W. de LIMA MONTEIRO
Symposium on Microelectronics Technology and Devices - SBMicro, 2009, Natal - RN. Proceedings of SBMicro 2009 - ECS. Pennington - New Jersey - EUA : The Electrochemical Society Transactions, 2009. v. 23. p. 537-544

11) **Semiconductor Microcavitiy: an intrinsic optical transistor**
E. A. Cotta.
24th Symposium on Microelectronics Technology and Devices, Natal, Novembro 2009.

12) **Self-consistent Optimization of Multi-Quantum Well Structures by a Genetic Algorithm.**
Roberto Yuji Tanaka, Angelo Passaro, Nancy Mieko Abe, Gustavo S. Vieira, Stephan Stephany
17th Conference on the Computation of Electromagnetic Fields - COMPUMAG 2009, November 22-26, 2009, Florianópolis, SC, Brasil.

13) **Control of the localization of self-assembled quantum dots**
C. G. Pankiewicz, P. T. Valentim, B. R. A. Neves, Paulo S. S. Guimarães, M. P. Pires, P. L. Souza
14th Brazilan Workshop on the Physics of Semiconductors, Curitiba, março de 2009.

14) **Exciton-photonic modes interaction in microcavity pillars**
C. A. Parra-Murillo, A. G. Silva, P. T. Valentim, J. S. V. Morais, F. Plentz, Paulo S. S. Guimarães, H. Vinck-Posada, B. A. Rodriguez, M. S. Skolnick, A. Tahraoui, M. Hopkinson
14th Brazilan Workshop on the Physics of Semiconductors, Curitiba, março de 2009.

15) **Dual behavior quantum dot infrared photodetectors**
D. Alvarenga, T. Gebhard, P. L. Souza, P. S. S. Guimarães, K. Unterrainer, M. P. Pires, G. S. Vieira, J. M. Villas-Boas
14th Brazilan Workshop on the Physics of Semiconductors, Curitiba, março de 2009.

d) Summit

1) Participation in the summit of coordinators of various INCTs in Campinas in March 2009.

e) Publications

1) **Current bi-stability in a weakly coupled multi-quantum well structure: a magnetic field induced "memory effect".**
W. H. M. Feu, J. M. Villas Boas, L. A. Cury, P. S. S. Guimarães, G. S. Vieira, R. Y. Tanaka, M. P. Pires, S. M. Landi and P. L. Souza
Journal of Physics. D, Applied Physics, v. 42, p. 1/145109-7/145109, 2009.

2) **Intraband Auger Effect in Quantum Dot Structures**
T. Gebhard, K. Unterrainer, D. Alvarenga, P. S. S. Guimarães, J. M. Villas Boas, M. P. Pires, G. S. Vieira and P. L. Souza
International Journal of Modern Physics B, v. 23, p. 2872, 2009.

3) **Growth and capping of InAs/GaAs quantum dots investigated by x-ray Bragg-Surface diffraction**
R. O. Freitas, A. A. Quivy, S. L. Morelhão
Journal of Applied Physics, v. 105, p. 036104, 2009.

4) **Effects of confinement on the electron-phonon interaction in $Al_{0.18}Ga_{0.82}As$/GaAs quantum wells**
R. R. O. Morais, I. F. L. Dias, M. A. T. da Silva, D. F. Cesar, J. L. Duarte, S. A. Lourenço, E. Laureto, E. C. F. da Silva, A. A. Quivy
Journal of Physics - Condensed Matter, v. 21, p. 155601, 2009.

5) **Influence of quantum-dots density on average in-plane strain of optoelectronic devices investigated by high-resolution X-ray diffraction**
R. O. Freitas, B. Diaz, E. Abramof, A. A. Quivy, S. L. Morelhão
Physica Status Solidi A – Applications and Materials Science, v. 206, p. 1714, 2009.

6) **Exciton behavior in GaAs/AlGaAs coupled double quantum wells with interface desorder**
E. M. Lopes, J. L. Duarte, L. C. Pocas, I. F. L. Dias, E. Laureto, A. A. Quivy, T. E. Lamas
Journal of Luminescence, accepted for publication.

7) **Comparison of some theoretical models for fittings of the temperature dependence of the fundamental energy gap in GaAs**
R. R. O. Morais, I. F. L. Dias, J. L. Duarte, E. Laureto, S. A. Lourenço, E. C. F. da Silva, A. A. Quivy
Brazilian Journalof Physics , accepted for publication.

8) **Study of the influence of indium segregation on the optical properties of InGaAs/GaAs quantum wells via split-operator method**
S. Martini, J. E. Manzoli, A. A. Quivy
Journal of Vacuum Science and Technology B, accepted for publication.

9) **Microelectonics Technology and Devices SBMicro 2009. 1. ed.**
D. W. de LIMA MONTEIRO , O. Bonnaud, N. I. MORIMOTO
Pennington - New Jersey - EUA: The Electrochemical Society Transactions, 2009. v. 23. 623 p.

10) **Markovian and Non-Markovian Light-Emission Channels in Strained Quantum Wires**, V. Lopez-Richard, J. C. Gonzalez, F. M. Matinaga, C. Trallero-Giner, E. Ribeiro, M. Rebello Sousa Dias, L. Villegas-Lelovsky and G. E. Marques, Nanoletters, **Publication Date (Web):** August 10, 2009 (Letter). **ISSN:** 1530-6984, 9, 9, p. 3129-3136.

11) **Self-consistent Optimization of Multi-Quantum Well Structures by a Genetic Algorithm.**
Angelo Passaro, Roberto Yuji Tanaka, Ademar Muraro Jr, Gustavo Soares Vieira, Nancy Mieko Abe
Accepted for publication in IEEE Transactions on Magnetics.

12) **A self-consistent analysis of subband alignment in a superlattice with one larger well**
Roberto Yuji Tanaka, Angelo Passaro, Nancy Mieko Abe, Gustavo S. Vieira, Stephan Stephany.
Accepted for publication in International Journal of Applied Electromagnetics and Mechanics.

13) **Terahertz-field-induced tunneling current with nonlinear effects in a double quantum well coupled to a continuum**
Marcelo Z. Maialle, Marcos H. Degani, Justino R. Madureira, and Paulo F. Farinas
J. Appl. Phys. **106**, 123703 (2009).

14) **Nanoscale dislocation patterning by scratching in an atomic force microscope**
F. A. Ponce, Q. Y. Wei, Z. H. Wu, H. D. Fonseca-Filho, C. M. Almeida, R. Prioli, D. Cherns
J. Appl. Phys. **106**, 076106 (2009).

15) **Numerical calculations of the Quantum States in Semiconductor Nanostructures**
Marcos H. Degani and Marcelo Z.Maialle
Journal of Computational and Theoretical Nanoscience, accepted for publication.

16) **Multiple-photon peak generation around 10μm in quantum-dot infrared photodetectors**
Marcos H. Degani, Marcelo Z. Maialle, Paulo F. Farinas, Nelson Studart, M.P. Pires and P.L. Souza
Submitted to Physical Review B.

17) **Growth of linearly ordered arrays of InAs nanocrystals on scratched InP.**
H. D. Fonseca Filho, C. M. Almeida, R. Prioli, M. P. Pires, P. L. Souza, Z. H. Wu, Q. Y. Wei and F. A. Ponce
Journal of Applied Physics, accepted for publication.

f) Products and Processes

1) Software

QWS-ver4.0 – Computer program to design and analyse semiconductor nanostructures using the Method of Finite Elements. This is the multiplataform (Windows and Linux) version of the program and has essentially all the resources of the Windows version. The QWS- ver4.0 has a friendly graphic interface in which the sample parameters are introduced and the calculation can be performed with or without self-consistency. The results (wavefunctions and probability density) are graphically presented. The calculated data, effective mass, potential profile, wavefunctions, probability densities and oscillator strengths are saved in files. The program was developed in C++, ANSI, the graphic interface was developed in QT, 4th version, the finite elements calculations use a library named SDK-LEVSOFT developed at IEAv. This product will be available for INCT-DISSE members through our intranet.

2) Patent deposited

1) D. W. De Lima Monteiro, Thiago de Oliveira de Freitas, Luciano Nakamura, Self-reconfigurable system of phtovoltaic solar cells and other photodetectors. Patent deposited at INPI-Instituto Nacional para Proteção Industrial
2) A. P. Singulani, O. P. Vilela Neto, M. A. Pacheco e P. L. Souza, Method for optimizing the performance of solar cells Método Number 0000221000435517 - 27/01/2010.

3) Video

Video “Ver o Invisível” (See the Invisible) developed for scientific dissemination. The video was exhibited in several events: PUC POR UM DIA (PUC for a day) in May 2009, Semana da Ciência (Week of Science) in September 2009 and Semana do Conhecimento (Knowledge Week) at the Federal University of Minas Gerais in October 2009.

VI. Activities for human resources building and training

a) Courses

1) In 2009 the DISSE members of São Paulo State: Nelson Studart, Paulo Farinas, Marcelo Maialle, Marcos Degani, Gustavo Soares Vieira and Alain Quivy, submitted to FAPESP a proposal for the organization of a school called ***Advanced School on Optoelectronics: Fundamentals and Devices.*** The main objective of the school was to awake interest among graduation students to a subject with an enormous potential for bringing products, and therefore patents generation and spin-offs creation. The development of new optoelectronic products needs a strong basis on devices physics, materials synthesis, device fabrication techniques and characterization. All these subjects were included in the program. However the proposal was not approved. The team will try it again in the present year.

2) **Summer School on Fundamentals and Materials for Novel Sensors**

INCT-DISSE co-organized that school together with the Technische Universität Braunschweig, offering it to graduation students of all Brazil. The school occurred in the campus of PUC-Rio, from July 13 to July 24, 2009, and was followed by 25 graduation students.

3) **IEEE/CASS Workshop on Image Sensors**

The group of the Engineering School of UFMG from INCT-DISSE, organized together with the Engineering School of UFRJ from INCT-NAMITEC events on 24/11/2009, in Rio de Janeiro, and on 26/11/2009, in Belo Horizonte, with three international invited speakers (Prof. Dr. Albert Theuwissen, Harvest Imagem/Belgium – TU-Delft/Netherland; Dr. Carlos Mendoza, Anafocus/Spain; Mr. Simon Schneiter, CSEM/CSEM-BR/Switzerland/Brazil).

4) **II Workshop on Effects of Ionizing Radiation in Electronic and Photonic Devices for Space Applications.**

Members of IEAv from DISSE have participated in the organization of this Workshop which the private sector and the academia have joined. Short courses and seminars were given by researchers from different universities, research centers as well as from industry. The companies which have participated are: Omnisys Engenharia Ltda., Equatorial Sistemas S.A., EQE – Tecnologia Eletrônica Qualificada Espacial e Com. Ltda., Opto Eletrônica S.A – OPTO e Mosaico Engenharia Eletrônica Ltda. This workshop received funds from FINEP/PEICE for the investigation of the effects of ionizing radiation on electronic and optical devices for space applications.

5) **International Symposium on Microelectronics Technology and Devices – SBMicro**

Aimposyum organized together with members of INCT-NAMITEC as part of the international conference *Chip on the Dunes*, in Natal-RN between 31/8 and 03/9/2009.

6) **New graduate course:**

In the graduate program of ITA a new area of studies is being created on sensors and attenuators by the members of IEAv, including the one from DISSE. The program involves:

- Advanced materials for sensors and metamaterials
- Fiber optic, integrated optical, infrared, magnetic and magneto-mechanical sensors.
- Signal preparation and measurement techniques
- Nanotechnology and MEMS;
- Computational modeling of physical phenomena
- Image processing and remote sensing

- Physics of semiconductor devices

b) Human resources building and training

One of the most important activities of the Institute is the human resources building and training in the themes of the project, considered of great strategic importance.

The human resources building and training within the project happens mainly through the scientific initiation (IC), master of science (M) and doctorate (D) students, and through the fellows of technological development (DTI) enrolled in the activities of the institute. During this first year there were 24 IC, 15 master, and 16 doctorate students, and 04 DTI fellows. Six master dissertations and one doctorate thesis have been presented in this first project year:

- **Doctorate thesis:**

1- Omar Paranaiba Vilela Neto , Engineering School – PUC-Rio, Presentation date: August 2009.
Title: "Projeto, otmização, simulação e predição de propriedades de nanoestruturas através de técnicas de inteligência computacional: Nanotecnologia computacional inteligente."

- **Master dissertations:**

1- Anderson Pires Singulani, Engineering School – PUC-Rio, Presentation date: August 2009.
Title:"Simulação e projeto de células solares com poços quânticos de GaAs/AlGaAs auxiliado por algoritmos genéticos."
2- Carlos Gabriel Pankiewicz, Physics Department, UFMG, Presentation date: March 2009. Title: "Localização de pontos quânticos semicondutores via nanolitografia por oxidação anódica".
3- Carlos Alberto Parra Murillo, Departamento de Física da UFMG, Presentation date: July 2009, Title: "Study of Semiconductor Heterostructures with Embedded Quantum Dots".
4- Kenya Aparecida Alves, ITA – CTA, Presentation date: September 2009.
Title: "Caracterização de Fotodetectores de Infravermelho a Poços Quânticos"
5- Germano Penelo, Institute of Physics, UFRJ, Presentation date: July 2009.
Título dissertação: "Crescimento e Estudo de Fotodetectores de Infravermelho de Pontos Quânticos Acoplados com Poços Quânticos Parabólicos"
6- Leandro Cupertino, Engineering School – PUC-Rio, Presentation date: August 2009.
Title: "Modelagem do módulo de Young em nanocompósitos através de inteligência computacional "

All the students and fellows enrolled in the project are listed below.

	Scientific Initiation			
	Name	**Institution**	**Advisor**	**Ended in**
1	Breno Lopes Campolina	Física, UFMG	Paulo Sérgio Soares Guimarães	February 2010

2	Renato Átila Silva Santana	Física, UFMG	Wagner Nunes Rodrigues	ongoing
3	Victor Shmidt Comitti	Física, UFMG	Franklin Matinaga	ongoing
4	Marina Bezerra Eiras Silva	Física, UFMG	Franklin Matinaga	ongoing
5	Ana Flávia Boaventura Ladeira	EE, UFMG	Davies William	ongoing
6	Pedro Felipe Leite Retes	EE, UFMG	Davies William	ongoing
7	Pedro Henrique Silva Miranda	EE, UFMG	Davies William	ongoing
8	Anna Baptista De Moraes A. Marim	Instituto de Física, UFRJ	Mauricio Pamplona Pires	ongoing
9	Alan Carlos Maioli	Instituto de Física, UFRJ	Mauricio Pamplona Pires	ongoing
10	Teo Camarotti	EE, PUC-Rio	Patricia Lustoza de Souza	ongoing
11	Luiza Schluz	EE, PUC-Rio	Patricia Lustoza de Souza	ongoing
12	André Abreu Calfa	EE, PUC-Rio	Marco Aurélio Pacheco	ongoing
13	Luis Ricardo Teixeira e Silva	EE, PUC-Rio	Marco Aurélio Pacheco	ongoing
14	Maria Helena Carvalho	DEM, PUC-Rio	Guilhermo Solorzano	ongoing
15	Rebeca	DEM, PUC-Rio	Guilhermo	ongoing

	Puetter		Solorzano	
16	Paulo Roberto Soledade Junior	Física, UNIFAP	Henrique Fonseca Filho	December 2009
17	Erveton Pinheiro Pinto	Física, UNIFAP	Henrique Fonseca Filho	ongoing
18	Daniel Takaki Ferreira	Instituto de Física, USP	Alain Quivy	ongoing
19	Victor Bernardo Chabu	Instituto de Física, USP	Alain Quivy	ongoing
20	Eduardo Sell Gonçalves	Instituto de Física, USP	Alain Quivy	ongoing
21	Fabricio C. Gomes	IEAV, CTA	Angelo Pássaro	ongoing
22	Wellington Palma Gonçalves	IEAV, CTA	Angelo Pássaro	ongoing
23	Vilmara Paixão de Sousa Barbosa	Física, UFAM	Eduardo Adriano Cotta	ongoing
24	Carlos Eduardo de Almeida Brito	Física, UFAM	Eduardo Adriano Cotta	ongoing
	Master			
	Name	**Institution**	**Advisor**	**Ended in**
1	Carlos Alberto Parra Murillo	Física, UFMG	Paulo Sérgio Soares Guimarães	16/Jul/2009
2	Marcos Flávio de Oliveira	Física, UFMG	Wagner Nunes	ongoing

	Silva		Rodrigues	
3	Leandro Cupertino	EE, PUC-Rio	Marco Aurélio Pacheco	July 2009
4	Anderson Singulani	EE, PUC-Rio	Marco Aurélio Pacheco	August 2009
5	Carlos Gabriel Pankiewicz	Física UFMG	Paulo Sérgio Soares Guimarães	October 2009
6	Thonimar Vieira de Alencar Souza	Física, UFMG	Franklin Massami Matinaga	ongoing
7	Germano Penelo	Física, UFRJ	Maurício Pamplona Pires	July 2009
8	Daniel Micha	Física, UFRJ	Maurício Pamplona Pires	February 2010
9	Rudy Kawabata	EE, PUC-Rio	Patricia Lustoza de Souza	ongoing
10	Barbara Figueroa	EE, PUC-Rio	Patricia Lustoza de Souza	ongoing
11	Kenya Aparecida Alves	IEAV, CTA	Gustavo Soares Vieira	September 2009
12	Paula Magda da Silva Roma	Física, UFAM	Eduardo Adriano Cotta	February 2010
13	Efrain Fernandes Marques	Física, UFAM	Eduardo Adriano Cotta	ongoing
14	José Maurício da Cunha	Física, UFAM	Eduardo Adriano Cotta	ongoing
15	André Luíz dos Santos	Física, USP	Euzi Conceição Fernandes da Silva	em andamento
	Doctorate			

	Name	Institution	Advisor	Ended in
1	Carlos Gabriel Pankiewicz	Física, UFMG	Paulo Sérgio Soares Guimarães	ongoing
2	Pablo Thiago Valentim	Física, UFMG	Paulo Sérgio Soares Guimarães	ongoing
3	Déborah Reis Alvarenga	Física, UFMG	Paulo Sérgio Soares Guimarães	ongoing
4	André Gonçalves Lima	Física, UFMG	Paulo Sérgio Soares Guimarães	ongoing
6	Germano Penelo	Física, UFRJ	Mauricio Pamplona Pires	ongoing
7	Omar Paranaíba Vilela Neto	EE, PUC-Rio	Marco Aurélio Pacheco	August 2009
8	Leandro Cupertino	EE, PUC-Rio	Marco Aurélio Pacheco	ongoing
9	Anderson Singulani	EE, PUC-Rio	Marco Aurélio Pacheco	ongoing
10	Alexandre Grilo	DEM, PUC-Rio	Guilhermo Solorzano	ongoing
11	Ana Cristina Vidal	DEM, PUC-Rio	Guilhermo Solorzano	ongoing
12	Geronimo Perz	DEM, PUC-Rio	Guilhermo Solorzano	ongoing
13	Martin Mendoza	DEM, PUC-Rio	Guilhermo Solorzano	ongoing
14	Natasha Midouri	DEM, PUC-Rio	Guilhermo Solorzano	ongoing

15	Patricia Gobi	DEM, PUC-Rio	Guilhermo Solorzano	ongoing
16	Álvaro Diego Bernardino Maia	Instituto de Física, USP	Alain Quivy	ongoing
17	Fernando Massa Fernandes	Instituto de Física, USP	Alain Quivy	ongoing
	DTI			
1	Marcela de Freitas Mendonça	IEAV, CTA	Gustavo Soares Vieira	ongoing
2	Rodolfo Felipe de Oliveira Costa	Física, UFMG	Gustavo Soares Vieira	Ongoing
3	Thiago Barçante	Física, UFMG	Gustavo Soares Vieira	December 2009
4	Petrus Bonato de Almeida	EE, UFMG	Davies William de Lima Monteiro	em andamento

The students and DTI fellows enrolled in the activities of the Institute act in areas of great strategic relevance. The formation of such human resources will surely contribute to the consolidation of the technology developed in the project through the eventual creation of spin-offs, or by incorporation in the research departments of industries, or even joining the many university centers yet in consolidation in the country.

It is important to remember that the activities of the Institute include not only basic research, but also the development of technologies yet incipient in the country.

VII. Perspectives

Promising perspectives are open with the creation and one year of operation of the INCT-DISSE. First, with the acquisition of the new equipment for growth of semiconductor samples it will be possible to grow better quality samples and produce competitive optoelectronic devices, as well as fully establish a center for epitaxial growth within the INCT-DISSE. Second, a very positive and motivating synergy has been created among the members of the Institute. Members with different background are all committed to fulfill the proposed four missions and to achieve together the best possible results. Both graduate and undergraduate students are very motivated with the perspectives of academic learning and technological development in collaboration with industry and with the activities of knowledge dissemination to society.

Some partnerships with industry were strengthened and new opportunities arose with new contacts with other companies. There are companies interested in participating in the effort for the production of the infrared photodetectors in Brazil, others interested in producing equipment which requires such devices and finally some interested in using the equipment for specific applications.

As for the theoretical aspects, the group that has developed the split operator method will now disseminate this knowledge to the other theoreticians of INCT-DISSE, since it is a valuable tool for computational modeling of semiconductor heterostructures.

Finally, it should be pointed out that the installation of modern equipment in Amapá (UNIFAP) and in Amazon (UFAM) has given a great impulse in the research activities in these two emerging institutions, allowing the nucleation of productive groups in science and technology.