ISSN:1983 7402

Use of a Cryogenic Probe Station for Measurement of Activation Energy of QWIPs

C. A. Delfino[1], M.F. Mendonça[1], G. S. Vieira[1], A. Passaro[1], F. M. Fernandes[2] and A. Quivy[2]
[1]EFA-E Instituto de Estudos Avançados – São José dos Campos, Brazil
[2]Instituto de Física, Universidade de São Paulo – São Paulo, Brazil

***Abstract* — Here we describe the actions taken for validating the use of a cryogenic probe station (down to 10 K) for the determination of carriers activation energy on semiconductor devices, and illustrate it for quantum well infrared photodetectors. The methodology used and back ground theory are described, besides the probe characterization that was needed for ensuring reliable measurements. Some good practices are also indicated. The results illustrate well how the performed setup characterization is important for the reliability of the measurements, especially when comparing activation energies with close values.**

Keywords—criogenic probe station, activation energy, QWIP.

I. Introduction

Some electronic devices, like photon detectors of infrared radiation, need cryogenic temperatures for operation and, consequently, must be tested also at such temperatures [1]-[2]. When testing a large number of devices on a wafer, it is not possible to wire bond all the devices, what asks for the use of a probe station, in this case, a cryogenic one. The use of probe stations for quantitative measurements, however, is not as straightforward as it may seems, specially a cryogenic one. It is necessary to be careful on measurements and know well the equipment in order to get reliable results. Here, we present characterizations performed in a Janis manual cryogenic probe station and exemplify its use with the measurement of activation energy of some quantum well infrared photodetectors, QWIPs. The measurements done show a small difference in the activation energy of two pieces of sample, which only can be taken as real due to the careful characterization performed previously. This fact illustrates clearly the importance of the performed setup characterization, for the reliability of the results.

II. Probe Station Description

The cryogenic probe station used is a Janis model CCR10 [3], specified for controlling the sample temperature between 10 K and 325 K, using a cold finger from a two stage closed cycle helium compressor. The temperature is monitored using standard Si diodes (model DT-670-CU) [4], which have accuracy specified as: ± 0.004 K at 4 K, ± 0.085 K at 80 K and ± 0.07 K at 270 K. There are such sensors attached: one below the sample mount, one on the radiation shield, one on the cold head first stage, and one on the cold head second stage. The probe station has 6 manually manipulated arms with triaxial connectors. Two of the arms have two connectors in each for reducing the effect of added resistance, from cables, on low resistance measurements (Kelvin configuration). The needles used are made of tungsten and are gold plated for better contact resistance. The probe also has a cold radiation shield. It is necessary for making it able of reaching the desired temperatures and for blocking the infrared radiation that, otherwise, would reach the devices under test, coming from the 300 K cryostat walls.

III. Verification of Equipment Characteristics and Methodologies Needed

Before performing final measurements on the devices, many tests were done on the experimental apparatus, and on the methodology applied for the measurements. The main tests performed are described below.

A. Electrical contact between needles and sample contact pads

When using a probe station, the contact resistance between the needles and the metallic film on the sample depends on the contact pressure, besides cleanness of needles and metallic surface on the sample. It was observed that a bad electrical contact between needle and pad may generate bad results even for a current versus voltage measurement made using four needles. Since the probe station is manual, not allowing for the determination of needle applied force, the operators must be well trained in order to assure good electrical contacts without excessively damaging the pads. A verification of measurements reproducibility must be performed, at least, when starting the measurements of each sample. It is done by repeating measurements after raising needles and putting than in contact again with the pad and by comparing measurements done with 2 and with 4 needles.

B. Thermal contact between sample and sample holder

The samples are placed over a gold plated cooper block connected to a cold finger (Fig. 1). It could be expected that putting the samples over the sample holder and mechanically fixing it would be enough for get the necessary thermal contact, but the results showed that it is not. For example, in Fig. 2, current versus time graphics, at constant voltage, are shown for the same QWIP device placed over the sample holder in different conditions: fixed laterally by metal blades, and without thermal grease; with the metal blades pressing the sample against the cooper block, but without thermal grease; with thermal grease, but without mechanical fixing; and with the metal blades pressing the sample against the cooper block and thermal grease on sample bottom. The measurements start only after sample holder temperature (measured by the sensor below the cooper block, Fig. 1) has stabilized, and immediately after the needles have been placed. It can be seen

ISSN:1983 7402

that the current, after stabilization, is quite different for each condition, having the lower current and higher reproducibility for the last condition, sample with thermal grease on its back and mechanically fixed.

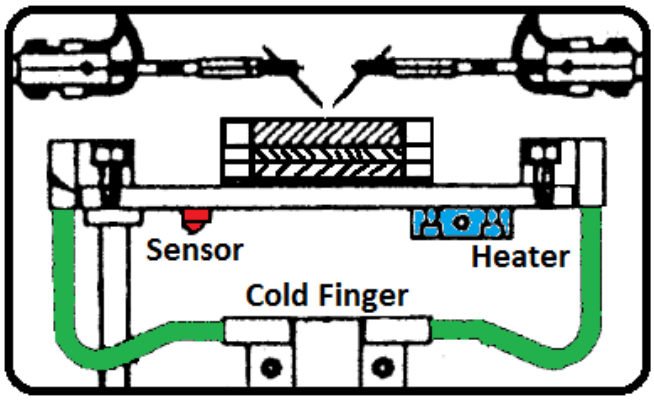

Fig. 1. Diagram of sample holder

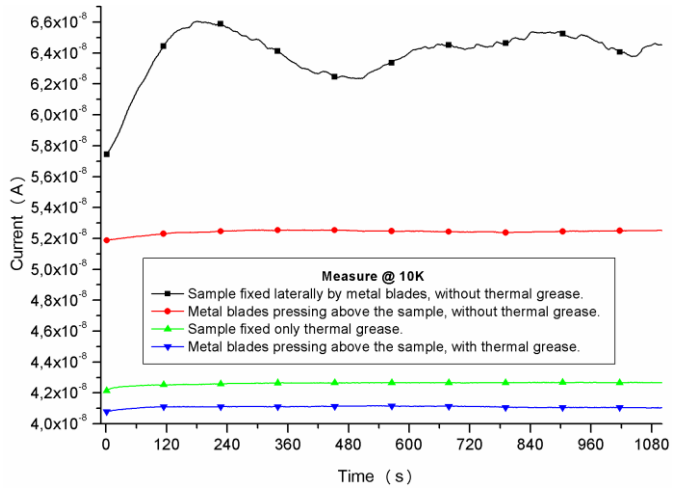

Fig. 2. Measured current of the same device, against time, for the sample fixed in different ways, with the sample holder at 10 K

It should be noted that the higher current obtained, in the cases where the thermal contact is bad, is not a transitory one, as could be expect, but stationary. We believe that the temperature raising comes from the heat injected on the device through the needles. Although the needles are also refrigerated, they are thermally connected to the radiation shield (with a temperature around 60 K), not to sample holder.

C. Temperature Uniformity over the Sample Holder

When making measurements like activation energy determination, the accuracy of sample temperature determination is of great importance, since it has a strong impact on the final values obtained.

The sensor used for the temperature controller, and the corresponding heater, are both located in the bottom part of the sample holder cooper block (Fig. 1). The unused pins of an already existing feedthrough were used for connecting extra three temperature sensors that were placed at the top of sample holder, as shown of Fig. 3, for mapping the temperature over the sample holder and comparing than to the equipment setpoint. The measurements were performed for 10 temperatures between 10 K and 100 K, and the temperature variation on the top of the sample holder was found to be below 0.2 K, for all temperatures, and the largest difference between the top temperature and the set point was below 0.7 K. The largest temperature difference on the sample holder top and the largest difference between sensors on the top and the setpoint, as a function of set point temperature are shown on Fig. 4.

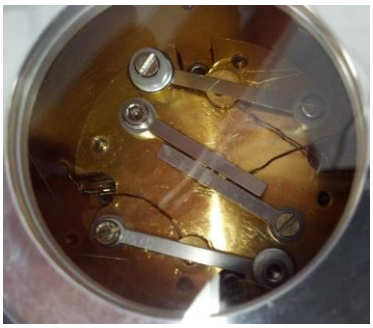

Fig. 3. Temperature sensors placed on sample holder

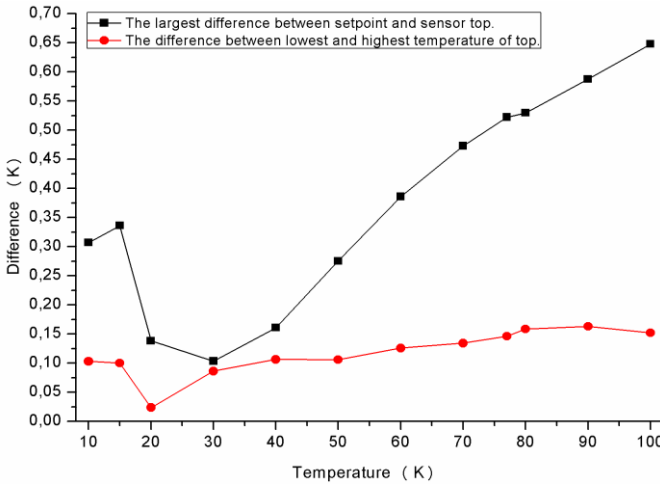

Fig. 4. Thermal variation between sensors

IV. MEASURING THE ACTVATION ENERGY OF QWIPS

A. Theoretical Background

A QWIP device is made of epitaxially grown of continuous layers of semiconductors of different gaps, on a given substrate. For a QWIP doped N, the conduction band profile can be modeled as a sequence of wells and barriers in the effective mass approximation [5]. If the barriers are large enough, the tunneling current can be neglected, and only the electrons thermally excited to energies above the barriers will contribute to the dark current of the devices. Although the current versus voltage, I-V, curve of such devices are clearly nonlinear, it presents a linear behavior for low enough bias. At such voltages, the current density can be expressed in the traditional way [6]-[7]:

$$\vec{J} = n(T)e\mu(T)\vec{E} \quad (1)$$

ISSN:1983 7402

Where *n(T)* is the density of free electrons (with energy above the barriers), *e* the electron charge modulus and *μ(T)* the electron mobility. It was stressed that the density of free electrons and the mobility are temperature dependent. Equation (1) gives the following equation for the low bias I-V curve:

$$I = n(T)e\mu(T)\frac{A}{l}V \qquad (2)$$

Where *A* is the device area and *l* is active structure length. The free electron density dependency with temperature can be expressed as an exponential term times a term that changes with temperature in a much slower rate, giving:

$$n(T) = a(T)e^{-E_a/kT} \qquad (3)$$

Where, E_a is the activation energy. The conductance of the sample for low bias can be taken from (2). Substituting (3) on the conductance expression and taken the logarithm on both sides lead to:

$$\ln(C) = \ln\left[a(T)e\mu(T)\frac{A}{l}\right] - \frac{E_a}{kT} \qquad (4)$$

Since the mobility also changes slowly with the temperature, a plot of ln(*C*) versus *1/T* will give, approximately, a decreasing straight line, with angular coefficient equal to E_a/k.

B. Measuments and Results

The measurements were done on devices processed on two pieces of the same wafer, with QWIP layers grown by MBE. The sample was grown on a semi-insulating GaAs substrate and is composed of 50 periods of a multi quantum well structure with 30 nm wide barriers of $Al_{0.21}Ga_{0.79}As$ and 5.6 nm wide well of GaAs, doped with Si at 10^{18} cm^{-3}. This structure was sandwiched between 1 μm wide contact layers, doped with Si at 1.4 x 10^{18} cm^{-3}.

Fig. 5 shows the I-V curves of one of devices measured with temperature ranging from 10 K to 100 K. From such curves, the conductance for low bias was taken by linear fitting (Fig. 6). Observe that the graphic on Fig. 6 is of current density versus voltage, J-V, what gives the conductance normalized by the device area. It was done since the devices fabricated on different sample pieces had different areas.

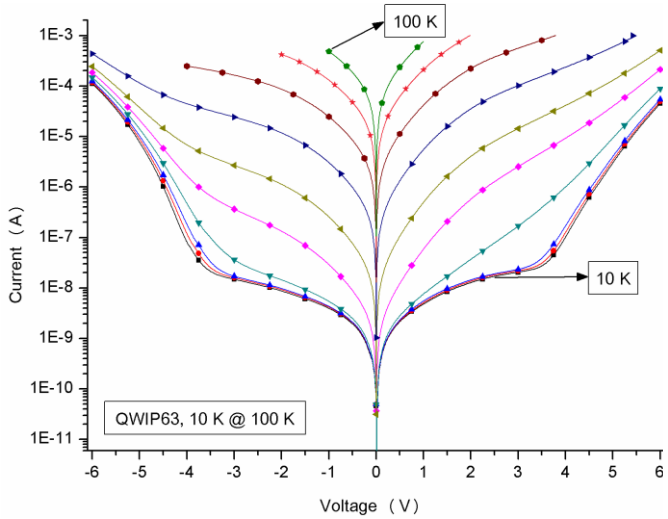

Fig. 5. Plot of I-V curves with temperatures ranging from 10 K to 100 K for a QWIP device

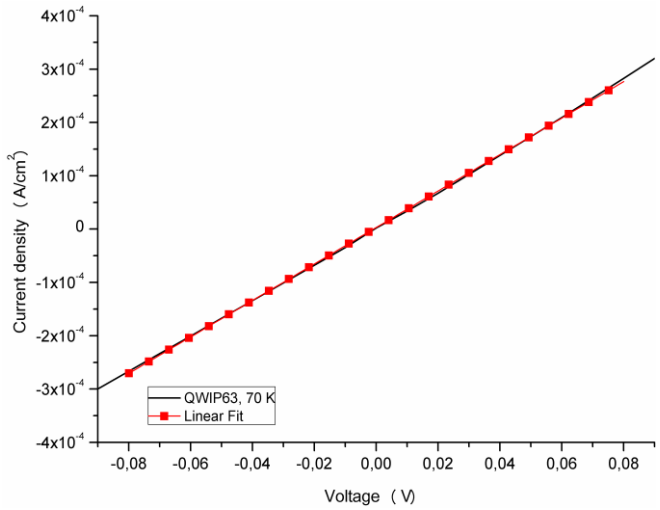

Fig 6.Linear fit of a J-V curve

Fig. 7 shows the logarithm of the normalized conductance versus *1/T* for 12 devices, six from each piece of the sample. Two regions are clear on the graphics. One of steeply decreasing of ln(C/A) with 1/T and other with the ln(C/A) nearly constant. If a linear fitting on the higher slop is made, and the activation energy is calculate from it, a value close to the theoretical one is found to all devices, but the values found for the devices on the same piece of sample are closer to each other than between devices of different pieces (table 1). One possible explanation for the difference measured is a small gradient on Aluminum concentration over the wafer, given similar values for devices closely spaced and a measurable, although small, difference for devices largely spaced.

It is important to note that, although the two sample pieces were placed together on the probe station, a gradient of few degrees on the sample holder, or similar temperature difference generated by bad thermal contact, could generate similar results, making the results inconclusive. It clearly shows the importance of the previous setup characterization, showing that such temperature difference does not exist, for making sure that the difference in activation energy is real, not a measurement artifact.

ISSN:1983 7402

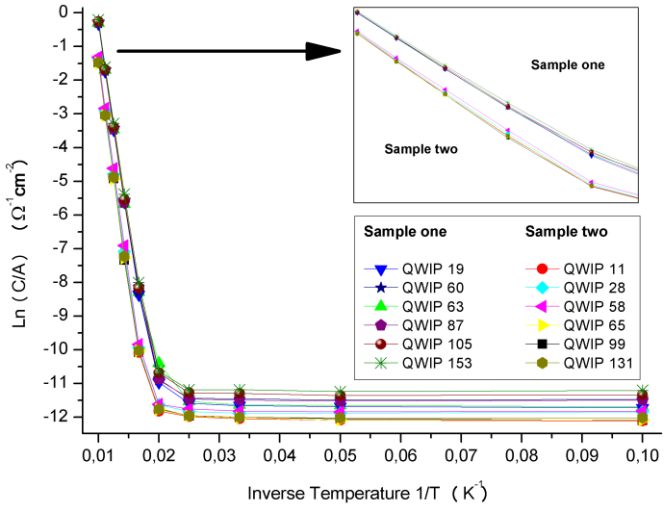

Fig. 7. Plot of normalized conductance versus inverse temperature for 12 devices

TABLE I. RESULTS

	QWIP	Linear Fit		Activation Energy
		Slope	Standard Error	
Sample one	19	-1234	12	0,106
	60	-1239	14	0,107
	63	-1256	4	0,108
	87	-1251	7	0,108
	105	-1229	11	0,106
	153	-1204	13	0,104
Sample two	28	-1337	16	0,115
	58	-1301	12	0,112
	65	-1347	13	0,116
	99	-1368	4	0,118
	118	-1360	12	0,117
	131	-1338	15	0,115

V. CONCLUSIONS

It has been shown that a set of characterizations were performed on a manually manipulated cryogenic probe station, giving crucial information and generating good practice guidance, which allows for reliably performing sensitive experiments like activation energy determination.

ACKNOWLEDGMENT

One of the pieces of the sample was processed at the Microfabrication Laboratory of LNNano, with great help of local staff, Angelo Luiz Gobbi and Maria Helena Piazzetta. We also would like to thanks Raquel Martins Villela Nunes, for help with the sample, and the financial support of FINEP (Fundos Setoriais), MCT, CNPq, FAPERJ and CAPES. This work received support from INCT-DISSE

REFERENCES

[1] HUDSON, R.D.JR., Infrared system engineering. New York: John Wiley and Sons Inc., 1969.

[2] A. ROGALSKI, "Quantum well photoconductors in infrared detector technology", Journal of Applied Physics, vol. 93, pp. 4355-4391, 2003.

[3] Janis Research Company, Inc – Model nº CCR10-2. Available in: <http://www.janis.com/Products/productsoverview/MicromanipulatedProbeStations/CryogenFreeMicromanipulatedProbeStations.aspx>. Acess: 08/13/2014.

[4] Lake Shore Cryotronics, Inc., "DT-670 Silicon Diodes", Available in: <http://www.lakeshore.com/products/Cryogenic-Temperature-Sensors/Silicon-Diodes/DT-670/pages/Specifications.aspx> Acess: 08/13/2014.

[5] R. Y. Tanaka, A. Passaro, N. M. Abe, L. K. Sperotto, D. M. Pedroso, G. S. Vieira, "Computer program for nanostructured semiconductor devices simulation" in 2013 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference, 2013.

[6] N. W. ASHCROFT; N. D. MERMIN, "Solid state physics". Austrália: Books/Cole Publ.; New York, NY: Holt, Rinehart and Winston, c1976. 826 p. ISBN 0-03-083993-9.

[7] B. F. LEVINE, "Quantum well infrared photodetectors", Journal of Applied Physics, vol. 74, R1R81, 1993.