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PRELIMINARY EVALUATION OF QUANTUM HALL EFFECT DEVICES BY PHOTOREFLECTANCE SPECTROSCOPY

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Abstract - Internationally, an electrical resistance standard is based on quantum Hall effect devices and, usually, these are based in AlGaAs/GaAs heterostructures. In this work we report the study of a set of quantum Hall effect devices by photoreflectance spectroscopy at 300 K. An optical signal associated to the electric field build in the 2DEG region was found and it was used to identify the samples with superior electron mobility. With this study, is possible to offer an excellent nondestructive method before to make electrical contacts and magnetoresistance measurements.

Keywords: quantum Hall effect, AlGaAs/GaAs heterostructure, photoreflectance spectroscopy.

1. INTRODUCTION

Quantum Hall effect (QHE) devices usually consist of AlGaAs/GaAs hetrerostructures because is possible to observe the quantum phenomena at higher temperature and lower magnetic field that other systems [1, 2]. In this kind of devices the control over the quality crystal (thickness, the doping level and Al concentration) is very important to obtain a two dimensional electron gas (2DEG) with high mobility [3, 4].

To explore the quality crystal and determine the electrical properties is common to make classical Hall measurements (~ 1 T and 77 K) and therefore electrical contacts are necessary. This mean that the surface will be destroy to know the electronic properties before to carry out quantum Hall measurements.

On the other hand, photoreflectance spectroscopy is a fast, nondestructive and contactless method to evaluate some parameters. In addition, is possible to perform measurements at room temperature.

In this work we present the result of the optical characterization of a group of QHE devices based on AlGaAs/GaAs heterostructure. We use PR technique to find the signal originated by the 2DEG region and estimate the electric field magnitude here. Finally, we found an inverse relationship between the electric field and the electron mobility such that the sample with minor electric field in the 2DEG region presented the higher mobility.

2. EXPERIMENTAL

2.1. QHE devices

The AlGaAs/GaAs heterostructures were grown by molecular beam epitaxy (MBE) technique, on GaAs substrates. A GaAs buffer layer (BL) with thickness denoted by Θ was deposited, followed by an undoped $Al_xGa_{1-x}As$ spacer layer with thickness Σ. Next, a $Al_xGa_{1-x}As$ barrier layer β doped with Silicon, and finally all structures were capped with 10 nm of GaAs with the same Si-doping concentration. Furthermore, to improve the quality crystal of the samples a super lattice (30 repetitions of 10 Å GaAs - 10 Å GaAs) was deposited just after of substrate. A schematic representation of the AlGaAs/GaAs structure is shown in Figure 1.

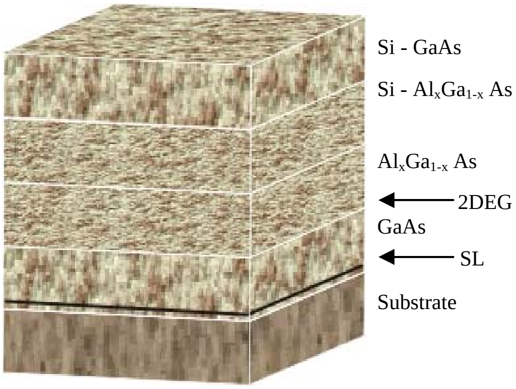

Fig. 1. Schematic picture of QHE devices studied in this work.

Is possible to separate three groups according to some parameters:

- ➢ The first group (from M1 to M5) has the similar parameters except by the spacer layer thickness and M4 has the SL below 0.6 µm of 2DEG region (AlGaAs/GaAs heterojuntion).

- ➢ The second group (M6, M7 and M8) have a thin layer of $In_{0.02}Ga_{0.98}As$ with 5, 10 y 20 nm, respectively. This layer is deposited inside the buffer layer to 25 nm close to 2DEG region.

➢ In the last group, we changed the substrate type (semi-insulate and n-doped) and we changed from As_4 to As_2 molecular beam to explore the quality crystal evolution by photoreflectance.

Table 1 shows the main characteristics of the QHE devices studied in this work. The nominal thickness of the buffer and spacer layer corroborated by reflectance measurements, Al concentration in AlGaAs layer, doping level and mobility magnitudes in the 2DEG obtained by conventional Hall measurements.

Sample	Sub	**Θ** (μm)	**Σ** (nm)	**β** (nm)	**Al** (%)	**Si** (cm^{-3})	**μ** (cm^2/V.s)
M1	SI	3	6	100	28	$1.5x10^{18}$	74 500
M2	SI	3	6	100	35	$1.0x10^{18}$	107 000
M3	SI	3	12	100	35	$1.3x10^{18}$	116 000
M4	SI	3	18	100	35	$1.5x10^{18}$	97 000
M5	SI	2	500	100	30	$1.2x10^{18}$	600
M6	SI	2	12	100	35	$9.0x10^{17}$	8100
M7	SI	2	12	100	35	$2.2x10^{18}$	3100
M8	SI	2	12	100	35	$2.0x10^{18}$	1210
M9	SI	2	10	200	36	$1.0x10^{18}$	68100
M10	SI	2	10	200	32	$1.0x10^{18}$	65250
M11	SI	2	10	50	32	$1.0x10^{18}$	66300
M12	N	2	10	200	36	$1.0x10^{18}$	60055
M13	N	2	10	200	32	$1.0x10^{18}$	70084
M14	N	2	10	50	33	$1.0x10^{18}$	70100

Table 1. QHE devices parameters. The nominal thickness of the buffer Θ, spacer Σ and the barrier layer β. The Al and Si concentration. The mobility μ in the 2DEG.

2.2.- Photoreflectance spectroscopy

Photoreflectance spectroscopy (PR) is a technique based on the modulation of surface and interfacial electric fields build in semiconductors materials, through the recombination of photo-generated carriers produced by the action of light with higher energy than the band gap of the material.

The modulation can easily be accomplished by varying some parameters, associated with the sample or the experimental system, in a periodic fashion and measuring the corresponding normalised change of the optical properties. It is possible to modulate a variety of parameters, i.e. the wavelength of light, temperature, stress applied or electric field in the sample studied. The electromodulation techniques are based on the modulation of the electric field. One of the electromodulation techniques is photoreflectance spectroscopy where the varying parameter is the internal (built in the structure) electric field.

In the PR, the modulation of the electric field in the sample is caused by photoexcited electron-hole pairs created by the pump source (usually laser) which is chopped with a given frequency. The photon energy of the pump source is generally above the band gap of the semiconductor being under study. The mechanism of the photo-induced modulation of the built-in electric field F_{DC} is explained in Figure 2, for the case of an n-type semiconductor. Because of the pinning of the Fermi energy E_F at the surface, there exists a space-charge layer. The occupied surface states contain electrons from the bulk (Fig. 2a). Photoexcited electron–hole pairs are separated by the built-in electric field, with the minority carrier (holes in this case) being swept toward the surface. At the surface, the holes neutralize the trapped charge, reducing the built-in field from F_{DC} to F_{DC}-F_{AC}, where F_{AC} is a change in the built-in electric field (Fig. 2b).

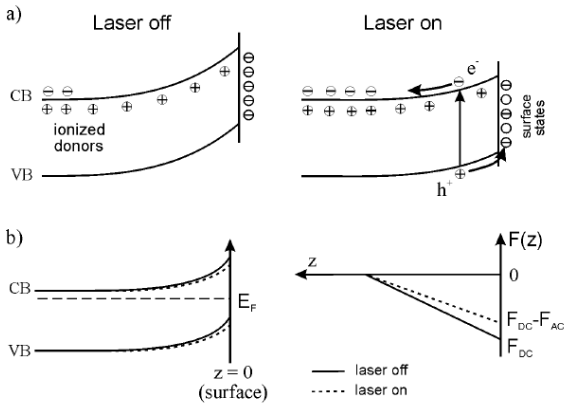

Fig. 2. Schematic representation of the photoreflectance effect and the photoinduced changes in (a) electronic bands and the (b) surface bulit-in electric field.

Photoreflectance spectroscopy can be classified into two categories, high- and low-field regimes, depending on the relative strength of certain characteristic energies.

In the high electric field limit Aspnes and Studna showed that the PR line shape has the following asymptotic form [5]

$$\frac{\Delta R}{R} \approx (E-E_g)^{-1}\exp\left(-\frac{\Gamma(E-E_g)^{1/2}}{(\hbar\Omega)^{3/2}}\right)\cos\left(\frac{2}{3}\left[\frac{E-E_g}{\hbar\Omega}\right]^{\frac{3}{2}}+\theta\right) \quad (1)$$

where E_g is the semiconductor band gap, Γ is the broadening parameter, θ is a phase factor, and $\hbar\Omega$ is a characteristic electro-optic energy given by

$$\hbar\Omega = \left(\frac{e^2 F_{\text{int}}{}^2 \hbar^2}{8m}\right)^{1/3} \quad (2)$$

where e is the electron charge, F_{int} is the internal electric field strength, and m is the interband reduced mass involved in the transition.

From Eq. 1 we note that a clear signature of the existence of intense internal electric fields in semiconductor samples is the presence of damped oscillations at energies above the band gap of the semiconductor being under study, termed Franz–Keldysh oscillations (FKO). By analyzing these oscillations it is possible to determine the strength of the internal electric fields present in the studied samples.

According to Eq. 1, the FK oscillations extremes occur at energies given by

$$\frac{2}{3}\left[\frac{E_j - E_g}{\hbar\Omega}\right]^{\frac{3}{2}} + \theta = j\pi \cdots\cdots j = 1,2,.. \qquad (3)$$

Equation 3 can be rearranged as

$$E_j = \hbar\Omega F_j + E_g \qquad (4)$$

where

$$F_j = \left[\frac{3}{2}\pi\left(j-\frac{1}{2}\right)\right]^{2/3} \qquad (5)$$

in Eq. 3 we set $\theta = \pi/2$ which corresponds to a three-dimensional critical point.

Based on Eq. 3 the energy of the extremes E_j associated with FKO were plotted against the index number F_j. Next, we obtained the GaAs band-gap value from the ordinate to origin, while from the slope the electric field strength was evaluated, according to Eq. 4. The calculated values for F_{int} are summarized in Table 1. The values obtained for the band-gap energy are around 1.42 eV, which are very close to the accepted value for GaAs at room temperature.

PR measurements were performed by means of a standard experimental setup, see fig. 2. The probe beam was generated by the monochromatized light of an 100W tungsten halogen lamp, focused on the sample. The laser beam is chopped with the frecuency of 200 Hz. The light reflected from the sample is detected by a silicon photodiode. In order to prevent the detection of laser light, a longpass glass filter was used in front of the detector. Three different lasers were used as modulation sources alternatively: HeNe (632.8 and 543.5 nm) and HeCd (325 nm).

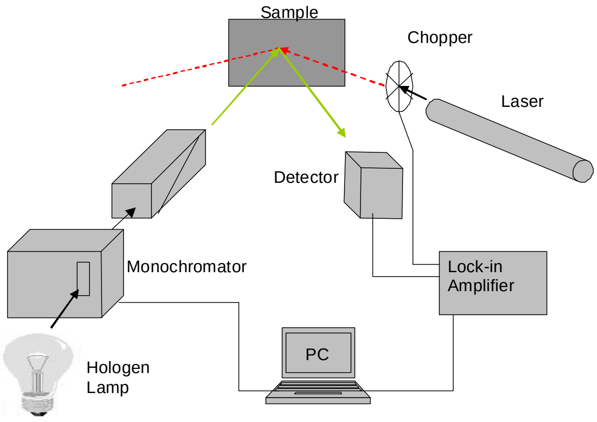

Fig. 3. Experimental set-up to photoreflectance measurements.

2.3.- Classical Hall measurements

Hall measurements were performed at 77 K to evaluate the mobility of the samples with a current of 0.1 mA in a magnetic field of 0.5 T. The samples used were provided with In contacts deposited by thermal evaporation. Triangular patterns were defined by using a shadow mask. The samples were alloyed in N2 atmosphere at 450 °C by 30 s. The current-voltage characteristics exhibited ohmic behavior at room temperature and 77 K. The device was bonded using indium balls and cooper wires.

3. RESULTS AND DISCUSSION

The most important parameter on QHE devices is the mobility of the 2DEG region although this magnitude is limited by many factors associated to the quality crystal like dislocations, carbon-related impurities, Si ionized atoms, etc. A sign of the existence of these factors is the electric field strength in that region.

A first question to answer is: what PR signal is originated by the 2DEG? and other: what electrical properties are associated to that signal? next: how is possible use it to evaluate the QHE devices?

Typically the PR spectra exhibit two signals at 1.42 eV and ~1.85 eV associated to the bandgap energy of GaAs and AlGaAs, respectively. The Franz Keldysh Oscillations (FKO) are usually observed above the bandgap transitions whose extremes (max-min) are useful to calculate the electric field magnitude [6-12]. As we can see on the fig. 4, above to 1,42 eV two kind of FKO are observed, with short and wide period, marked as A and B respectively. The origin of these FKO have been discussed because some people establish that the B signal is associated to the 2DEG [7, 8] but in fact exist evidence that it is created by the surface layer [9-12]. The signal C is originated by the AlGaAs layers.

In order to identify the signal originated by the 2DEG interface we changed the source of modulation to modify the penetration depth. Using laser with emission at 325 nm, 543.5 nm and 632.8 nm we obtain signal originated by indirect modulation from 100 nm, 2000 nm and 3500 nm of depth, respectively [13], Fig. 5 shows the PR spectra of M4 obtained. Is possible observe the disappearance of the A signal when the 325 nm laser is used which suggest that the A signal is originated by an interface more depth than 100 nm. This confirms that this signal is originated by the 2DEG because M4 has 112 nm of AlGaAs layer and 10 nm of GaAs layer over the 2DEG interface.

Fig. 6 shows the PR spectra of M2, M3 and M4 samples obtained with the 543.5 nm wavelength laser. There are differences at the B signal region associated to the surface electric field but the signal A and C are similar for all.

PR spectra of the second group are shown on the Fig. 7. These samples have a thin layer of $In_{0.02}Ga_{0.98}As$ with 5, 10 y 20 nm, respectively. This layer is deposited inside the buffer layer very close (25 nm) to 2DEG region. At the same time as the thickness of the InGaAs layer increase the period of the FKO increase, consequently the electric field near to the 2DEG region increase too. These enhance of the electric field in that region, due to piezoelectric effect originated by the mismatch of the lattice constant between GaAs and InGaAs, affect the electron mobility of the QHE device, as we can see the table 1.

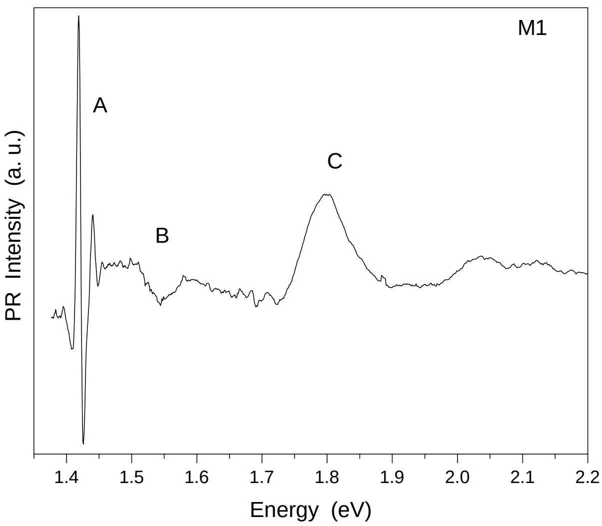

Fig. 4. PR spectra of M1 obtained with a 543.5 nm wavelength laser.

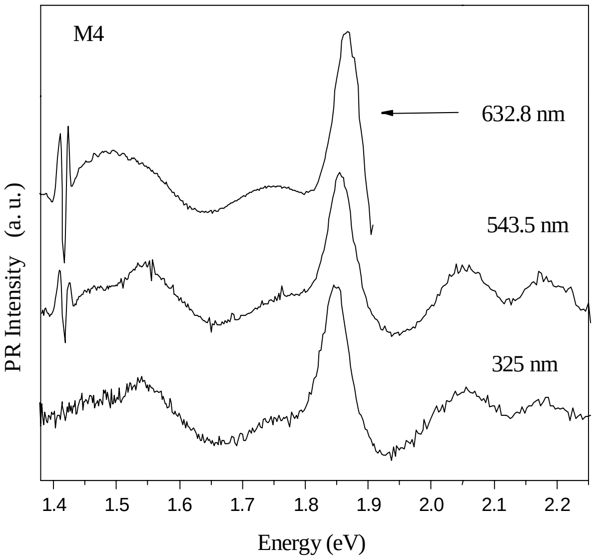

Fig. 5. PR spectra of M4 obtained with a 632.8 nm, 543.5 nm and 325 nm wavelength laser.

The last group has AlGaAs/GaAs heterostructures with a sample grown with As_4 and two with As_2 molecular beam over semi-insulate GaAs substrate and other similar samples grown over n-type GaAs substrate.

Fig. 8 shows the PR spectra of the samples grown on semi-insulate substrate. As we can see, there is a change on the Al concentration associated to the As-beam type, when we used As_2 the sticking coefficient of As-atoms increase and subsequently the Al content decrease. FKO about 1.42 eV are observed thence the electric field in the 2DEG region could be calculated. Similar situation is observed on samples grown over n-type substrate, see Fig. 9.

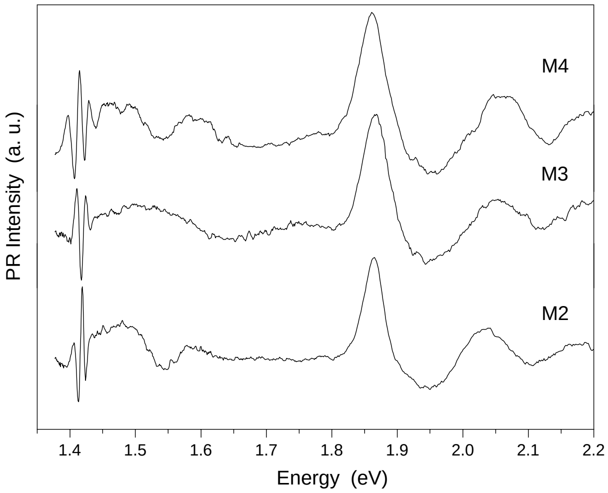

Fig. 6. PR spectra of M2, M3 and M4 obtained with a 543.5 nm wavelength laser.

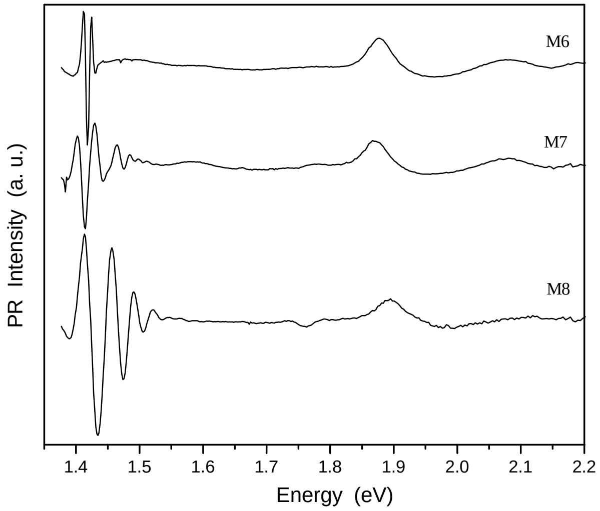

Fig. 7. PR spectra of M6, M7 and M8 obtained with a 543.5 nm wavelength laser.

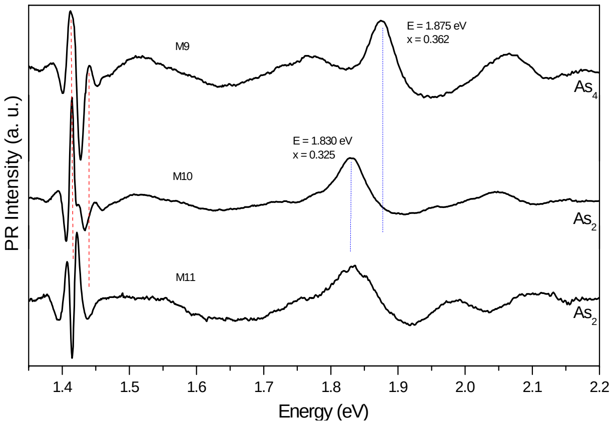

Fig. 8. PR spectra of M9, M10 and M11 obtained with a 543.5 nm wavelength laser.

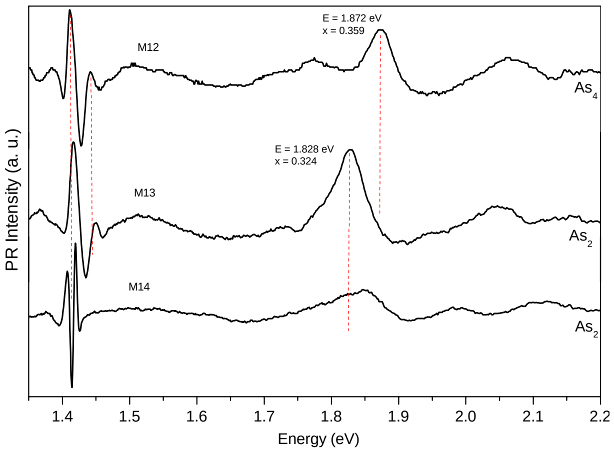

Fig. 9. PR spectra of M12, M13 and M14 obtained with a 543.5 nm wavelength laser.

Taking into consideration that the A signal is originated by the 2DEG is possible to calculate the electric field magnitude and plot it versus the electron mobility at 77 K. Fig. 10 shows the relationship between the electron mobility and the electric field for samples from both first and third groups.

PR spectra of M9, M10 and M11 showed oscillations with higher period than previous samples as evidence of higher electric field strength. Considering only the optical information is possible to affirm that the mobility is low, Hall measurement was congruent, as we can see in the inset of fig. 10.

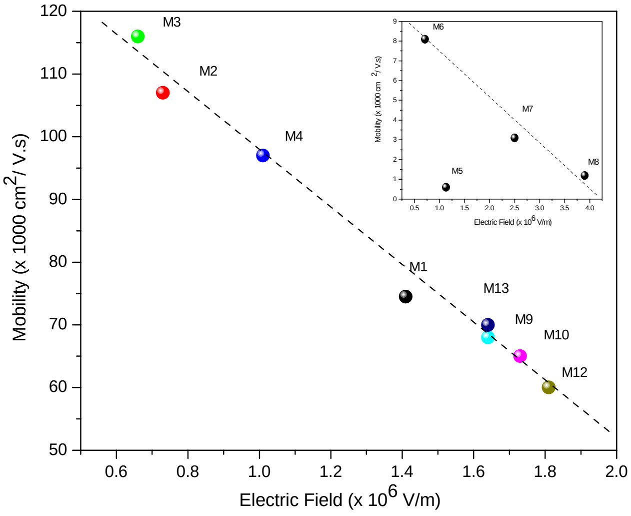

Fig. 10. Electron mobility at 77 K vs, the electric field strength in 2DEG region.

4. CONCLUSIONS

With this study is possible to affirm that photoreflectance spectroscopy is a useful tool to evaluate the internal electric field and estimate the electron mobility by a fast and not destructive way. Thus, is possible to know the electrical properties of QHE devices previous to make electrical contacts and quantum Hall measurements.

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