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Determination of surface electric potential by photoreflectance spectroscopy of HEMT heterostructures

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ABSTRACT

We studied a set of AlGaAs/GaAs heterostructures with high-mobility two-dimensional electron gas by room temperature photoreflectance spectroscopy. Electron mobility from 8.8 to 9.6×10^4 cm/V s was found by Hall effect measurements at 77 K.We carried out PR measurements with two lasers as modulation source: 543 and 325 nm. The spectra showed Franz–Keldysh oscillations (FKO) in two regions: short period FKO from 1.42 to 1.44 eV and broad oscillations in the range from 1.42 to 1.75 eV. The first oscillations are associated to the internal electric field in 2DEG region; the lowest calculated strength corresponded to the sample with the maxima electron mobility. The broad oscillations are unaffected modulation wavelength, which is indicative that they are originated in the surface cap layer. The magnitude of the surface electric field (465–503 kV/cm) from this region was used to calculate the potential profile of the edge of the conduction band by nextnano software. We found a surface electric potential around 0.7 eV, which affects the band structure until to a depth of about 50 nm. On the other side, when the surface is passivated by $(NH_4)_2S_x$ treatment the broad FKO disappear of PR spectra.

1. Introduction

Usually high-electron-mobility transistor AlGaAs/GaAs heterostructures contain the two-dimensional electron gas (2DEG) located close to the surface. Therefore, the electronic characteristics of the device can be affected by the properties of the surface. In order to eliminate chemical instability that may cause undesired effects it is well established that the surfaces of semiconductor-based devices have to be treated properly. Frequently, the surfaces of semiconductor devices are passivated in order to stabilize their chemical nature and to eliminate reactivity. $(NH_4)_2S_x$ [1], Si [2] and organic self-assemble monolayer (SAM) [3] have been used for coating GaAs-based devices. The effect of the surface on the electronic properties of a 2DEG has been studied by classic and quantum Hall effect measurements [3,4]. Specifically, the relationship between the surface and internal electric fields with electron mobility is the most important, but this option is not the best one because the structure has to be perturbed with the electrical contacts.

On the other hand, photoreflectance spectroscopy (PR) is a technique that has been widely used for the study and characterization of semiconductor devices structures [5–9]. Some reports have been focused to determine the origin of Franz–Keldysh oscillations (FKO) that are usually observed in the PR spectra. Now we know that wide-period FKO above energy gap of GaAs are associated to surface electric fields and short-period FKO are originated by the internal AlGaAs/GaAs interface [8–10].

In this work, we studied a set of heterostructures by PR measurements in order to determine the charge densities at the surface and, by using this information simulate the conduction band behavior in order to calculate the surface electric potential.

2. Experimental

The heterostructures were grown on semi-insulating GaAs (1 0 0) epiready wafers by molecular beam epitaxy (MBE). For sample M1, after the oxide-desorption process, a 1 μm-thick GaAs buffer layer was deposited at 680 °C, followed by a 7 nm undoped $Al_xGa_{1-x}As$ spacer layer and then a80-nm-thickSi-doped AlGaAs barrier. A second spacer layer, 7 nm-thick, of undoped $Al_xGa_{1-x}As$, was subsequently deposited. Lastly the structure was capped with 25 nm undoped

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Fig. 1. Layers structure of sample M3. M2 does not have the capping layer (2 nm–GaAs:Si). M1 does not have two layers: 10 nm–AlGaAs and 2 nm–GaAs:Si. Aluminum concentration for all samples was $x=0.36$.

GaAs. The Si concentration of the barrier layer was 1.4×10^{18} cm^{-3} and the nominal Al concentration was 36%. The structure of sample M2 is similar to that for M1, except that an intermediary layer of 10 nm-thick AlGaAs was inserted in the middle of the AlGaAs:Si barrier. M3, consists of a similar structure to M2, but an additional 2 nm-thick GaAs cap layer doped with Si (5×10^{17} cm^{-3}) was grown, see Fig. 1.

Hall measurements were carried out at 77 K with a current intensity of 100 mA and under a magnetic field of 0.5 T. Room temperature PR measurements were carried out employing and experimental setup similar to those described elsewhere [7]. With a 543 nm line of solid-state laser as the modulation source with a power density of 80 mW/cm^2 chopped at a frequency of 200 Hz. An Acton monochromator with a 0.5 m focal distance and a Spec-10 CCD camera system of Princeton Instruments were used. Alternatively, a second laser was used, 325 nm-HeCd MellesGriot laser at the pump-beam power density of 15 mW/cm^2. The probe beam was obtained from a tungsten–halogen lamp (DH-2000 ocean optics) with a spot size fitted to obtain a power density of 1 μW/cm^2.

Passivation process of the samples was performed under a similar way to those described elsewhere [1]. First, the surface was etched by a $C_3H_4(OH)(COOH)_3$–H_2O: H_2O_2 (5:1) solution and then thoroughly rinsed in deionized water. Finally, the etched samples were dipped into a solution of $(NH_4)_2S_x$ treatment.

3. Results and discussion

Fig. 2 shows the PR spectra of the three samples obtained with a 543 nm laser as the modulation source. As we can see there are two kind of FKO: a short-period oscillations in the range from 1.42 to 1.45 eV, which was labeled as A (A-FKO); and another broad oscillation from 1.42 to 1.70 eV marked as B (B-FKO). Besides, at 1.87 eV a PR signal associated with the AlGaAs band gap transition is observed. All spectra of Fig. 2 have a very similar line shape, which is indicative that neither the doped capping layer nor the intermediate AlGaAs layer originates substantial changes in the electric fields strength.

In order to determine the strength of the internal electric fields associated with the FKO we employed the asymptotic Franz–Keldysh modulation theory. In this model the energies E_j of the

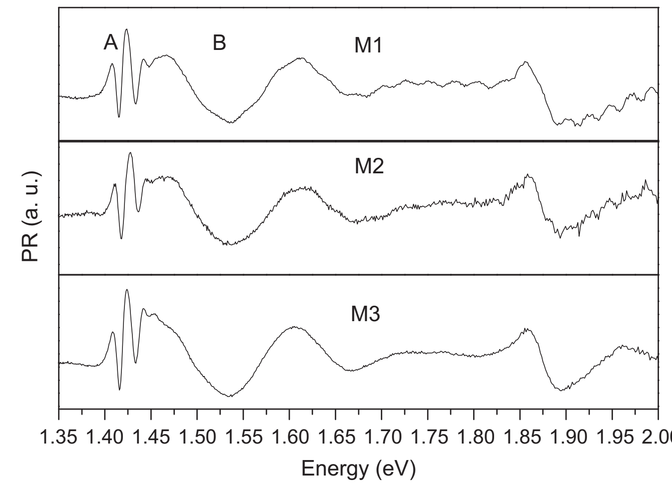

Fig. 2. PR spectra taken with the 543 nm line as modulation source. As we can see, there are two kind of FKO: one with short-period from 1.42 to 1.45 eV labeled with the letter A (A-FKO) and other with broad-period from 1.42 to 1.70 eV marked with the letter B (B-FKO).

Table 1
Concentration n_H and electron mobility μ_H obtained by Hall measurements at 77 K.

Sample	n_H (10^{11} cm^{-2})	μ_H (cm^2/V s)	$F_{\rm int}$ (kV/cm)	F_S (kV/cm)	N_S (10^{12}/cm^{-2})	ϕ_s (eV)
M1	9.32	88 413	19.0	503	3.64	0.703
M2	8.35	96 291	16.4	465	3.36	0.701
M3	9.30	93 785	18.4	468	3.39	0.699

Surface electric field F_S and internal electric field F_{int} obtained by FKO analysis. N_S and ϕ_s are the charge density and electric potential on the surface, respectively.

FKO extremes can be fitted to [11]

$$j\pi = \frac{\pi}{2} + \left(\frac{4}{3}\right)[(E_j - E_g)/\hbar\Theta]^{3/2} \tag{1}$$

where j is the index and E_j is the photon energy of the jth extremum, E_g is the energy gap of GaAs (for this case). $\hbar\Theta$ is the characteristic electro-optic energy and can be calculated by

$$\hbar\Theta = \left(e^2F^2\hbar^2/2\mu\right)^{1/3} \tag{2}$$

where e is the electron charge, F is the electric field strength and μ the interband reduced mass involved in the transition.

Eq. (1) can be rearranged as [12]

$$E_m = \hbar\Theta X_j + E_g \tag{3}$$

where $X_j = [3\pi/4(j-(1/2))]^{2/3}$.

As we can see, Eq. (3) corresponds to a linear function with a slope $\hbar\Theta$ and the intersection E_g, which can be determined by a fit linear of the experimental dates.

Finally, the electric field magnitude can be calculated by

$$F = \sqrt{\frac{2\mu(\hbar\Theta)^3}{e^2\hbar^2}} \tag{4}$$

The A-FKO signal was analyzed using the PR spectra obtained with the wavelength 543 nm laser and for the B-FKO signal analysis the spectra obtained with the wavelength 325 nm laser was used. The extremum positions of the A-FKO and B-FKO are plotted according to Eq. (3), as shown in Fig. 4(a and b), respectively. The values obtained for the electric field strength are presented in Table 1. From the A-FKO analysis we obtained an internal electric field ($F_{\rm int}$) that goes from 16.4 to 19.0 kV/cm,