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IMPURITIES IN GaAlAs-GaAs HETEROJUNCTIONS METASTABLE CHARACTER OF Si STATES AND MAGNETODONORS


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Résumé
A partir d’expériences de transport sous pression hydrostatique (système à gaz) nous mettons en évidence le caractère métastable du gaz d’électrons bidimensionnels dans les hétérojonctions GaAs-GaAlAs. Le gel magnétique des électrons bidimensionnels sur les donneurs dans ces hétérostructures avec couche non dopée (spacer) est alors étudié expérimentalement et le résultat est comparé à la théorie. Nous montrons en particulier que, pour rendre compte de ce type de magnéto-donueur, il est nécessaire d’introduire l’écrolement de l’interaction coulombienne entre électrons 2D et donneurs.

Abstract
Using transport experiments under hydrostatic pressure (gas pressure system) we demonstrate the metastable character of the two dimensional electron gaz in GaAs-GaAlAs heterojunctions. Magnetic freeze-out of inversion electrons into donors in heterostructures with a spacer has been investigated experimentally and compared with the theory. We show that the inclusion of screening of the Coulomb interaction between electrons and donors is essential for the description of magneto-donor energies.

Introduction
We have studied GaAs-GaAlAs heterostructures with a spacer using hydrostatic pressures, high magnetic fields and time-dependent temperature variations. This allowed us to demonstrate the metastable character of Si-donor states and their influence on the inversion electrons in GaAs layer.

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The density of 2D electrons in GaAs/Ga$_{0.65}$Al$_{0.35}$As as a function of temperature under different pressures. The results were obtained as the sample was cooled.

Figure 1 shows a typical variation of the 2DEG density $N_s$ when the sample is cooled down from 300K to 77K under different pressure values. The behaviour of $N_s$ reflects that of the free electron density $n$ in the Si doped GaAlAs layer. The decrease of $N_s$ with increasing pressure $P$ is due to an increase of the binding energy of the Si level in GaAlAs. The decrease of $N_s$ when the temperature $T$ is lowered happens only above 120K, i.e in the temperature range in which the thermal activation of $n$ is observed. Below this temperature $N_s$ and $n$ are practically constant. This behaviour is a consequence of the large lattice relaxation character of the Si level: when the energy barrier for electron capture cannot be overcome, the occupancy of the Si states cannot be modified even when their thermal activation energy is changed.

This picture is confirmed by experiments in which the pressure is varied at 77K. As shown in Fig. 2, the variation of the pressure (at least in the range 0-10Kbar) does not change $N_s$, the latter depends only on the pressure value at which the sample has been cooled. Fig. 2 shows that it is possible to obtain for each pressure different values of $N_s$. This possibility to obtain several stable states for one value of $P$ and $T$ means that the sample is out of thermodynamical equilibrium. It is then clear that the sample is in a metastable state at low temperatures. Using an appropriate gas-pressure cycle (cooling the sample from 300K to 77K at a given pressure and then changing the pressure to its final value) we can change the 2DEG density in the same sample at will.

In Figure 3 we report the variation of $N_s$ at $P=0$ when the sample is heated from 77K to 240K. The three curves correspond to the three pressures at which the sample was cooled to 77K before releasing pressure to zero. The temperature was raised at a rate of about 1K/min. We observe that up to about 120K, $N_s$ does not depend on $T$. The increase of $N_s$ observed at 120K is due to time-dependent processes: at a constant temperature $N_s$ increases with increasing time which reflects the lattice relaxation character of the Si donor level. The three curves join together at about 160K. Above this temperature $N_s$ is not time dependent and has the same value as the one measured at room temperature under zero pressure. The
transition from the metastable conditions to the conditions of thermodynamical equilibrium is thus clearly pointed out: in the low temperature region (up to 120K) the time necessary to obtain the equilibrium between the conduction band and the deep Si states in GaAlAs is so long that the redistribution of electrons is metastable. In the range 120-160K this time is about the measurement time, which allows one to observe a relaxation of $N_s$; above 160K the equilibrium is reached immediately.

As said previously, the observed metastable behaviour of the 2DEG is a consequence of the large lattice relaxation character of the deep Si level in the Si doped GaAlAs layer. We can therefore imagine that similar experiments can be performed on bulk GaAlAs in order to demonstrate the metastable character of Si states. Unfortunately, the pressure effect on the band structure is similar to that of alloying GaAs with Al and transport experiments under pressure on bulk GaAlAs with $x > 30\%$ can involve difficulties similar to those occuring in the study of samples rich in Al: the transport experiments do not give reliable results at temperatures lower than 100-150K [1]. This is a consequence of the decrease of mobility, related to the electron transfer into L or X minima of the conduction band.

A possible way to avoid these difficulties is to study the electron behaviour in inversion layer which reflects the behaviour of free electrons in GaAlAs: in this case whatever the Al content, the 2D electrons have a high enough mobility to enable transport measurements at low temperature.

It has been recently demonstrated by using magneto transport techniques [5] that, if the thickness of the spacer layer is not too large ($d < 250 \text{ A}^\prime$), one can observe bound magneto-donor states in the quasi two dimensional electron gas of GaAs-H. These bound magneto-donor states are due to the Coulomb interaction between Si donors in the Si doped GaAlAs layer and the 2D electrons. The magnetic freeze-out of the 2D electrons into magneto-donor states is observed in Ultra Quantum Limit (UQL), in which the inversion electrons occupy only the lowest Landau level. To reach the UQL with available magnetic fields requires low electron density $N_s$. As explained in the first part of the paper, this is obtained by using hydrostatic pressure. The binding energy of magneto-donors has been determined from the temperature dependence of $N_s$ in the freeze-out regime, at different magnetic field values. The experimental values of magneto-donor binding energy $E_a$ for four different intentionally doped GaAs-H with different values of the spacer thickness $d$ are shown in Fig. 4: $E_a$ increases with magnetic field and is lower when $d$ is larger, indicating that we deal with states related to Si donors on the other side of the spacer.
In Figure 5, we have reported the experimental activation in sample 3, measured at the same pressure, for which \( N_s \) has been varied by changing the sample cooling speed. In this case one deals with the same spacer thickness and Figure 5 shows that \( E_a \) increases with decreasing \( N_s \), or some other quantity related to it.

The characteristic parameter for the problem is \( \gamma = \hbar \omega_c / 2Ry* \), where \( \omega_c = eB/m* \) is the cyclotron frequency and \( Ry* \) is the effective Rydberg. In the theoretical study of the magneto donor states we have used a variational procedure \((0 < \gamma < 3)\). For the donor ground state we took the trial function, \( \psi(p,z) = \psi(p) f(z) \), in which the transverse motion (parallel to the interface) is described by a product of atomic-type and magnetic-type two-parameter function, \( \psi(p) = A \exp (-\alpha p - \beta p^2) \), while the longitudinal motion is described by \( f(z) = z \exp (-\beta_0 z/2) \).

**Fig. 6**: Theoretical binding energies of magneto-donors in GaAs-H with \( d = 150 \, \text{Å} \) and \( N_{de} = 6 \times 10^{10} \, \text{cm}^{-2} \) versus magnetic field, calculated for different surface densities \( N_s \) including screening.

We have assumed that the envelope \( f(z) \) is the same for the free and bound 2D electron [3]. We calculated the influence of the donor potential on the motion in the \( z \) direction by using the first order perturbation theory. For \( \beta_0 \) we used the Stern-Howard expression: \( \beta_0 = (48\pi m* e^2 (N_{de} + 11/32 N_s) / \kappa_0)^{1/3} \). \( N_{de} \) is the density of depleted charges. To describe the static screening of the Coulomb potential we used the Price procedure [4]. We have neglected the effect of the magnetic field on the screening. The binding energy is, in units of \( Ry* \): \( E_b = \gamma - T (\alpha, \beta) - U (\alpha, \beta) \) where \( T \) and \( U \) are trial averages of kinetic and potential energies respectively. For 2D electrons in the ground electric subband we used \( m* = 0.07 m_0 \), \( \kappa_0 = 12.56 \), \( Ry* = 5.8 \, \text{meV} \). In Fig. 6, we plotted calculated binding energies of magneto-donors for GaAs-H with a spacer \( d = 150 \, \text{Å} \), \( N_{de} = 6 \times 10^{10} \, \text{cm}^{-2} \), \( T = 6.2K \), and different values of \( N_s \). It appears clearly that at lower \( N_s \) the theoretical binding energy depends very strongly on surface density. This shows that the inclusion of screening is essential to reach an even rough agreement with the experimental values (sample 3 in Fig. 4). In Fig. 7, we show the calculated binding energies of magneto-donors for four values of \( d \) and \( N_s \) corresponding to the experimentally investigated samples. A comparison between these values and the data of Fig. 4 shows that, at high magnetic field i.e. away from the metal-nonmetal transition, the theory describes quite well the experimental values.

**Conclusion**: We have demonstrated the metastable character of the 2DEG in GaAs-H. The theoretical study we made of the magneto donor in GaAs with not too wide spacer shows that the inclusion of screening of the Coulomb interaction between Si ions and the inversion electrons is absolutely necessary for the description of the observed binding energies of magneto-donors.

**References**:


