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2DEG SPECTROSCOPY WITH RESONANT TUNNELING THROUGH SINGLE IMPURITY STATE

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We have used silicon impurities in an aluminum arsenide barrier to probe an adjacent two-dimensional electron gas (2DEG). A single impurity acts as a local spectrometer and scans the local density of states of the 2DEG. Magnetotransport experiments have been performed at low temperature with a magnetic field B applied along the direction of the current. Current–voltage characteristics strongly depend on B and reveal the formation of Landau levels (LLs).

Keywords: Tunneling; impurity; 2DEG.

1. Introduction

Two-dimensional electron gases (2DEG) in semiconductors have been intensively studied since the observation of the Quantum Hall Effect (QHE) in 1980. There have been many experiments that probed the macroscopic density of states (DOS) of these systems, but it is only recently that there is a possibility of probing the local density of states (LDOS).¹ A powerful tool in this field is the tunneling from 2DEG through a well-defined energy level corresponding to a localized state.

In this paper we present our investigations of the LDOS of a 2DEG by using the tunneling through a shallow donor level in GaAs/AlAs/GaAs heterostructure. AlAs is an indirect gap material with the minimum of the conduction band at X point of the Brillouin zone, while in GaAs the minimum is at Γ point. The bands are aligned in a way that AlAs layer forms a barrier for the electrons from Γ valley (solid line), and a quantum well (QW) for X valley electrons (dashed line), as one can see in Fig. 1. Silicon atoms, which are introduced by δ -doping in the middle of the AlAs layer, give rise to the existence of energy levels below the X -valley. When the heterostructure is biased, a 2DEG is formed at one side of the barrier and a tunneling process can occur from this 2DEG through a donor level, which thus acts

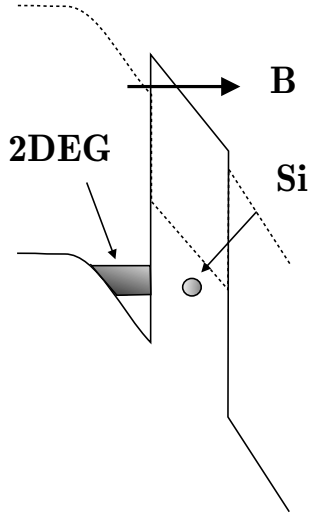


Fig. 1. Sketch of the structure.

as a spectrometer. This tunneling process occurs at reasonably low biases because the X -valley in AlAs is located at only 120 meV above the Γ valley in GaAs.

2. Sample Fabrication

The samples were grown by molecular-beam epitaxy on a (100)-oriented Si-doped n -type GaAs wafer ($N_d = 1 \times 10^{18} \text{ cm}^{-3}$). The active part of the heterostructure consists of a 10.2 nm AlAs barrier with δ -doping in the middle with concentrations of $N_\delta = 1 \times 10^{10} \text{ cm}^{-2}$, $5 \times 10^9 \text{ cm}^{-2}$ and without δ -doping for the reference samples. The barrier is separated from heavily-doped contacts ($N_d = 4 \times 10^{18} \text{ cm}^{-3}$) by 200 nm GaAs spacers in order to obtain high quality 2DEG. Using standard electron-beam lithography and etching techniques we have fabricated small mesa structures with lateral size varying from $500 \mu\text{m}$ to submicrometer diameters (down to 100 nm).

3. Large Mesas

Figure 2 shows current versus voltage curves measured at low temperature (4.2 K) on $500 \mu\text{m}$ width mesas with different δ -doping concentrations. The dashed $I(V)$ line corresponds to a typical result with an undoped barrier, the solid line to a doped one (10^{10} cm^{-2}). In the $I(V)$ curve of the doped pillar there is an important increase of the tunnel current at about 1 V. This is related to resonant tunneling through donor states.² The other current increase at about 2 V, present for both samples, is due to the tunneling through X -minimum quasi-localized levels.³ Within this scope we will concentrate on donor-related structures.

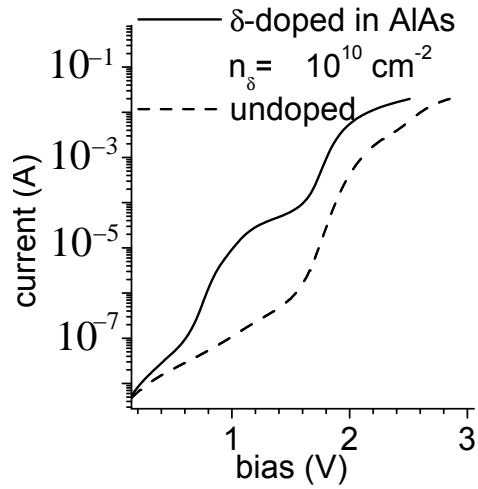


Fig. 2. $I(V)$ curves of large pillars.

4. Small Mesas

4.1. $I(V)$ curves at $B = 0$ T

If the lateral size of a mesa is reduced, the number of Si impurities inside the barrier decreases and individual contribution of each Si impurity can be resolved. Figure 3 shows the low-bias region of the $I(V)$ characteristics of two different samples that

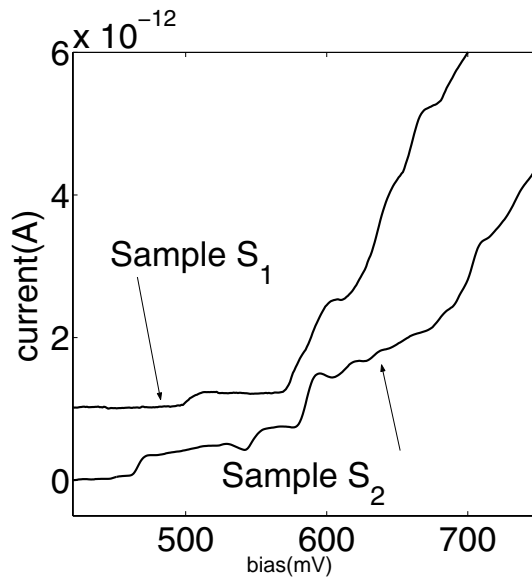


Fig. 3. $I(V)$ curves of small pillars; curve of sample S_1 has been shifted for clarity.

have been measured at very low temperature (30 mK). In both cases a succession of current steps is clearly observed.

Each step can be assigned to tunneling from an electron gas through individual Si atoms. The shape of a given step is a well-known signature of the two-dimensional nature of the electron gas in a QW. The threshold of a current step corresponds to the alignment of the Fermi energy of the 2DEG with the energy of the localized state. When the bias is increased further, the energy of the localized state becomes less than that of the first subband in the emitter and the current diminishes. The process of switching on and off the tunnel current is clearly seen in sample S_2 , where we observe both a threshold and a closure. The current plateau, between them, corresponds to a *complete* scan in energy of the 2DEG in the emitter. In case of other sample S_1 , we cannot see the whole scan, as there is another impurity that appears at about 570 mV.

4.2. $I(V)$ curves as a function of B

Let us now focus on the first step of sample S_1 in Fig. 3. Figure 4(a) shows the $I(V)$ curves of this sample measured in the presence of B ranging from $B = 0$ T (lower curve) up to $B = 5.8$ T (upper curve) with a step of $B = 0.1$ T. The curves are vertically offset by a constant current value for clarity. We observe the appearance of well-defined current peaks in magnetic field. These peaks correspond to the Landau quantization of the 2DEG. Landau levels $N = 0, 1, 2, 3, 4$ and 5 are clearly visible. In order to demonstrate that the observed peaks correspond to LLs, the voltage positions of their maxima have been extracted from the data and the magnetic field at which they appear has been reported in Fig. 4(b) and studied as a function of the bias. This allowed us to determine the voltage-to-energy ratio α as well as the electron density of the 2DEG under the assumption that the theoretical position of the Landau levels is given by

$$V_N = V_{cbe} - \alpha \times \hbar\omega_c \left(N + \frac{1}{2} \right), \quad (1)$$

where N is the Landau level index, V_N is the bias at which the N th LL is located, V_{cbe} is the bias at which the energies of the localized state and the bottom of first subband in the 2DEG are aligned and ω_c is the cyclotron frequency. The best fit in sample S_1 gives $\alpha = 15$ mV/meV and $V_{cbe} = 620$ mV. These values give $E_F = 8.1$ meV at $B = 0$ T and $n_s = m^* E_F / (\pi \hbar^2) = 2.3 \times 10^{11}$ cm $^{-2}$. The results are summarized in Table 1 for samples S_1 and S_2 and the best fit for sample S_1 has been reported both in Figs. 4(b) and 4(a). The mobility can be estimated if one notices that the LLs appear only above $B_c = 0.5$ T, which gives $\mu \simeq 1/B_c \simeq 2$ m 2 V $^{-1}$ s $^{-1}$.

There are some interesting features that are worth pointing out in the evolution of the LL peaks. First, there is a critical field B^* (a critical bias V^*) below (above) which a given LL is not resolved.¹ The corresponding critical points (B^* , V^*) for

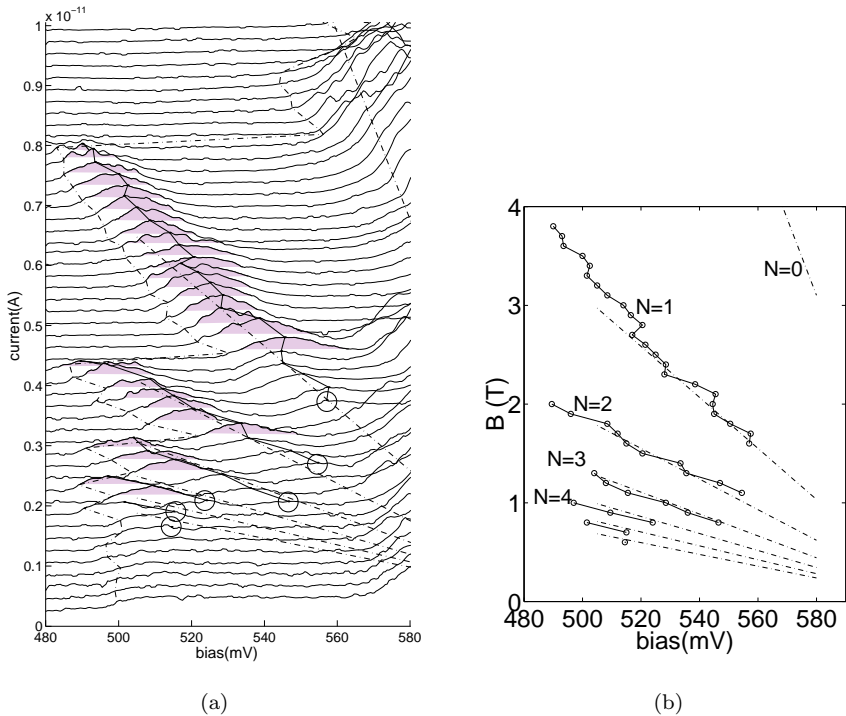


Fig. 4. (a) $I(V)$ curves for different B from 0 T to 5.8 T with a step of 0.1 T. Thick solid lines: maxima of the different peaks. The grey areas indicate the width at half maximum of these peaks. The large thick circles are the places where the peaks disappear. The thin dot-dashed line is the Landau level fit reported from Fig. 4(b). The thick dot-dashed line is the current threshold. (b) Fit of the $I(V)$ peaks. Open circles: positions of the peak maxima taken from Fig. 4(a). Thin dot-dashed lines: Landau level fit using Eq. (1). The LLs are labeled by their index N .

Table 1. Sample parameters.

Parameter	S_1	S_2	Parameter	S_1	S_2
Diameter(nm)	300	400	n_s (10^{11} cm^{-2})	2.3	1.6
α (mV/meV)	15	11	μ ($\text{m}^2 \text{ V}^{-1} \text{ s}^{-1}$)	2.0	2.0
E_F (meV)	8.07	5.72	V_{cbe} (mV)	620	530

the LLs $N = 1$ to 6 are indicated in Fig. 4(a) by large circles. For each of these points the quasiparticle lifetime τ is determined by $\omega_c \tau \sim 1$. Figure 5 shows τ^{-1} as a function of the energy $|E - E_F|$ obtained for the LLs $N = 1$ to 6. In order to determine the Fermi energy E_F , we assumed that the spectrometer energy is equal to E_F at the current threshold. The current threshold corresponds to the dot-dashed line in Fig. 4(a). As can be seen from Fig. 5, this method gives us a very large dispersion of the results. Although the decrease of the quasiparticle lifetime τ as a function of $|E - E_F|$ is undoubtedly observed, as predicted by the

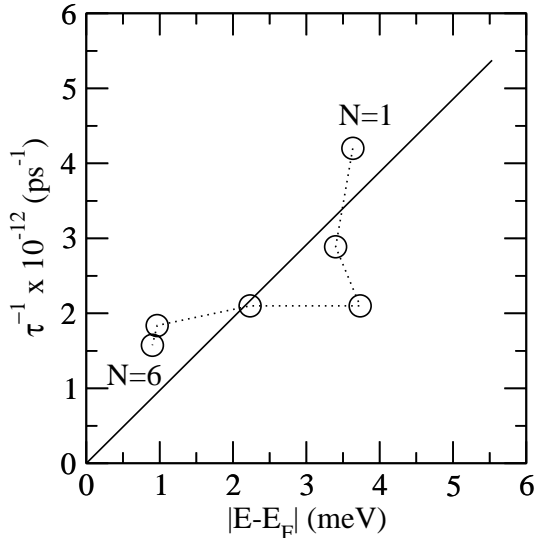


Fig. 5. The inverse of the quasiparticle lifetime τ as a function of $|E - E_F|$. The thick solid line is a guide for the eyes.

theory,⁴ it is impossible to fit our data either by a line or a parabola. We suggest that E_F should not be taken equal to the current threshold when $B > 0$. Indeed, most of the 2DEG states are states localized far away from the spectrometer and they give no current at all.⁵ Consequently, at the current threshold the energy of the spectrometer is already lower than E_F , which cannot be determined precisely from the $I(V)$ curves.

The second point to notice is that at $\nu \simeq 1$, where the first LL $N = 0$ reaches the Fermi energy the absolute shift of the LL peak is observed. The corresponding $I(V)$ curves are presented in Fig. 6. In this figure the magnetic field varies from 5 T to 12 T with a step of 0.25 T. The dot-dashed line corresponds to the $N = 0$ line of the LL fit used previously. If we assume that above $\nu = 1$ the $N = 0$ LL is unpolarized (we see no spin splitting) and that below $\nu = 1$ the LL is by contrast fully-polarized, the shift corresponds to a strong enhancement of the effective Lande g^* factor from 0 to a value greater than 7. This enhancement is attributed to the exchange interaction among electrons.⁶ We give only the low boundary of g^* here because the exact position of the upper LL, which is empty, cannot be determined below $\nu = 1$. The LL shift was observed systematically in all three samples studied, for both polarities. In one sample it was possible to observe clearly this effect for the second LL.

Finally we would like to point out that the LL peaks have a complicated shape made of several smaller peaks that evolve quickly as a function of the field B . This feature can be observed in Fig. 4(a) for $N = 1$ and in Fig. 6 for $N = 0$. The origin of these peaks remain unclear; possibly they originate from the lateral quantization

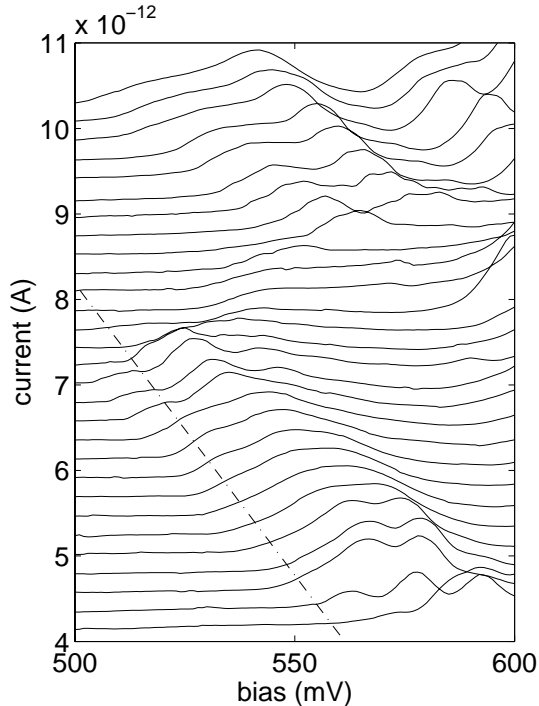


Fig. 6. $I(V)$ curves for B from 12 T (upper curve) up to 5 T (lower curve) with a step of 0.25 T. The peak corresponds to the first LL. The dot-dashed line is the fit of the first LL with the parameters used previously.

of the 2DEG states because of the finite size of the pillars. For instance, at $B = 1$ T, for an effective electrical diameter of $0.1 \mu\text{m}$, only $2e/h \times 10^{-14} \approx 5$ states remain per LL. This point will be checked using pillars of different sizes.

5. Conclusion

The measurements of the resonant tunneling through single donors allowed us to perform the spectroscopy of 2DEG, revealing Landau levels existence in the presence of a magnetic field and step-like density of states in zero field situation. The progressive appearance of the LLs shows that the particle lifetime decreases below E_F . The absolute shift of the lowest LL peak is observed for $\nu \simeq 1$, which is attributed to the strong enhancement of the effective Lande g^* factor. The fine structure of the LLs is not fully understood and needs further investigations.

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