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Spin filtering through a single impurity in a GaAs/AlAs/GaAs resonant tunneling device

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The Zeeman splittings of a Si shallow donor in AlAs and of a two-dimensional electron gas (2DEG) in GaAs are evidenced by resonant tunneling spectroscopy in submicrometer GaAs/AlAs/GaAs junctions. In magnetic field, the donor acts as a spin-sensitive probe of the spin-polarized density of states in the emitter. In the current-voltage characteristic the two splittings are resolved, which allows us to estimate the Landé g factors for the impurity $g_I = +1.96 \pm 0.16$ and for the 2DEG. Because of spin conservation in the tunneling between the 2DEG and the donor, the relative sign of the two g factors can be determined.

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Spin-polarized electronics and low-dimensional systems have been intensively studied in the last years. In this field, resonant tunneling through a zero-dimensional (0D) spin-split state is attractive because the 0D state can be used to implement a spin filter at the nanoscale. Such tunneling experiments have been used to observe directly the spin splitting of shallow impurities[1,2] and quantum dots (QD).[3–5] The 0D state can also be used to investigate the properties of the surrounding contacts, revealing local density of states (LDOS) fluctuations,[6,7] Landau-level (LL) formation,[8] or Fock-Darwin quantization.[9] The LDOS is also expected to carry information on the spin-orbit coupling[10] and spin lifetime.[11]

In this Rapid Communication, we demonstrate that a single impurity in a barrier filters the electron spins which tunnel from a two-dimensional electron gas (2DEG) when a magnetic field is applied. The spin conservation allows then to determine the Landé g factors of the impurity and of the 2DEG and to extract information about their relative signs. When doing this, we take advantage of the LDOS fluctuations on which spin effects are clearly superimposed.

The samples, described in detail elsewhere,[12] consist of GaAs/AlAs/GaAs junctions (see Fig. 1) with a Si δ doping intentionally introduced in the center of the AlAs barrier with a concentration of 3×10^9 cm^{-2}. The mesa structure investigated in this work has a diameter of $L = 900$ nm and contains about 25 Si impurities with different positions and energies. When bias is changed, the ground state (GS) of a single impurity related to the X valleys scans the local density of states of the 2DEG formed in the accumulation layer in front of the AlAs barrier. At low temperature, in the low bias part of the current-voltage characteristic $I(V)$, the contribution of the impurity with the lowest energy in the barrier is resolved.

Figure 2(a) shows the relevant region of the $I(V)$ curve, with the evolution of the two first current steps as a function of the temperature. These two steps are attributed to the two X_{xy} related states of the impurity, the degeneracy of which is lifted as suggested in Ref. 13. In the following, we concentrate on the first step. The threshold voltage V_{th} at ~ 1.09 V corresponds to the alignment of the Fermi energy ε_F in the emitter with the energy of the impurity GS. Therefore, its position depends on temperature. In contrast, the position of the LDOS fluctuations at higher bias is practically temperature independent. The small field $B = 12.5$ mT has been chosen to increase the LDOS at the Fermi energy and to extract more precisely the voltage-to-energy leverage factor α. Assuming a fast escape rate from the donor to the collector, the current through a discrete level is given by[1] $I(V) \propto 1/\{1 + \exp[\alpha^{-1}(V_{\mathrm{th}} - V)/k_B T]\}$, where the threshold voltage V_{th} corresponds to the intersection point of the $I(V)$ curves measured at different temperatures. Fitting the current onsets in Fig. 2, we obtain $\alpha = 12.75 \pm 0.75$ mV/meV (Ref. 14) and the width of the impurity spectrometer: $\Gamma = 60$ μeV. The position and height of the $I(V)$ thresholds for positive and negative biases (not shown here) confirm that the impurity is approximately in the center of the barrier. By applying a magnetic field $B_\parallel$ along the direction of the current, we ob-

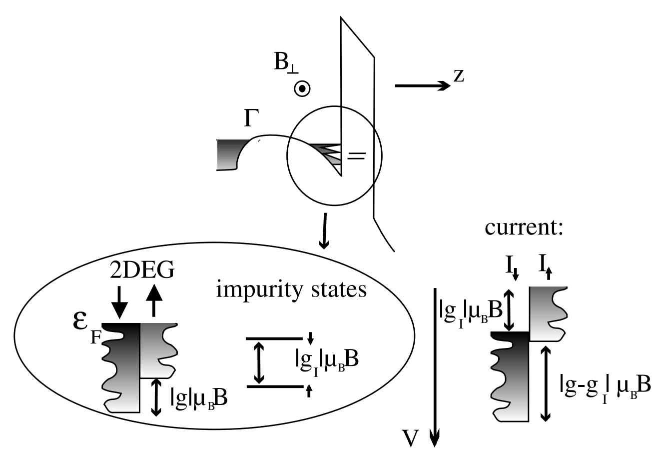

FIG. 1. Schematic of the conduction-band structure under an external bias. A Si donor in the barrier scans the local 2DEG. An in-plane magnetic field leads to a Zeeman splitting of the 2DEG and the impurity states by $|g|\mu_B B$ and $|g_I|\mu_B B$, respectively, while the LDOS shape remains unchanged. As an electron conserves its spin during the tunneling, the current onset splits as $|g_I|\mu_B B$ and the current closure (and the associated LDOS structures) splits as $|g_I - g|\mu_B B$. Schematic assumes $g<0$ and $g_I>0$ for clarity.

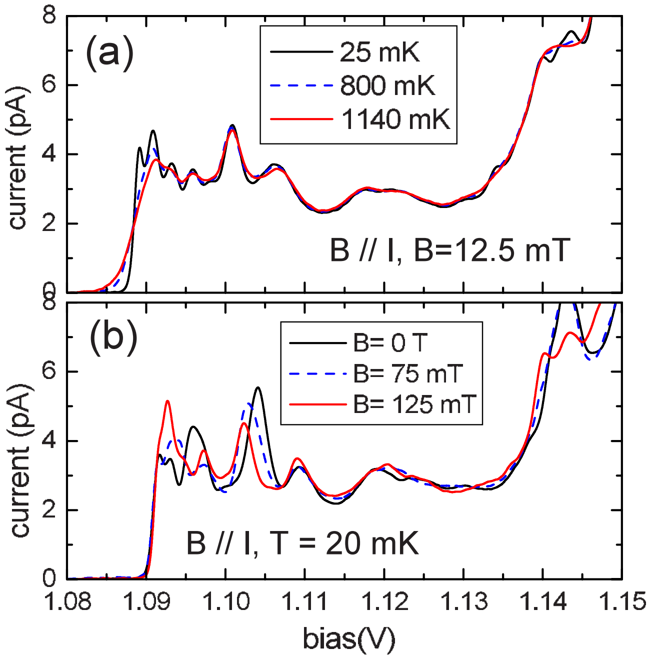

FIG. 2. (Color online) Evolution of the $I(V)$ curves (a) at different temperatures (b) when a magnetic field $B_{\|}$ is applied along the direction of the current.

served the formation of LLs at $B_{\|}=0.5$ T, which gives a mobility $\mu \sim 2$ $\mathrm{m^2\,V^{-1}\,s^{-1}}$. At higher fields, $B_{\|}\sim 10$ T, a LL shift[8,15] indicates the position of filling factor one, which gives the 2DEG electron density $n_s=2.4\times 10^{11}$ $\mathrm{cm^{-2}}$ and the associated Fermi energy $\varepsilon_F=8.5$ meV.

In order to check that the variation of current indeed reflects the LDOS fluctuations, detailed studies have been performed in the presence of a small field $B_{\|}$. Figure 2(b) shows that the fluctuations are extremely sensitive to $B_{\|}$ close to V_{th}. This sensitivity decreases at higher voltage, where the fluctuations of the LDOS are broadened and have a smaller amplitude. Following Ref. 16, we attribute this damping to the inelastic broadening $\hbar\gamma$ of the quasiparticle states in the 2DEG, induced by electron-electron interactions. The magnetic field sensitivity, observed in Fig. 2(b), is related to the size L_c^2 of the 2DEG region which is effectively covered by a coherent electron before it relaxes with the rate: $\gamma=D/L_c^2$, where D is the diffusion length and L_c is the coherence length. According to Ref. 17, L_c can be calculated using: $L_c=\sqrt{0.2(h/e)/B_c}$, where B_c is the half width at half maximum of the autocorrelation function of the sample conductance versus the magnetic field. Therefore we calculated the autocorrelation functions of $dI/dV(B)$ curves measured for magnetic fields in the range of 0–0.5 T at different fixed voltages, and then averaged over 10 mV intervals to perform an ensemble average. We found $L_c \leq 200$ nm$\ll L$ at $V\sim 1.095$ V (where we are limited by the magnetic field resolution) and $L_c\sim 150$ nm at $V=1.12$ V, approximately 2 meV below ε_F. Using the value of mobility, we estimated $\hbar\gamma\sim 0.2$ meV$\gg\Gamma$ at $V\sim 1.12$ V, thus confirming that the single impurity spectrometer width plays no role in this bias range.

The measured value of L_c helps to estimate which physical phenomena modify the LDOS fluctuation pattern when an in-plane magnetic field $B_\perp$ is applied. First, because the 2DEG has a finite width in the z direction, the in-plane B field is not completely decoupled from the orbital motion of the 2DEG. This induces an additional phase shift in the electron loops and therefore modifies the LDOS pattern observed at $B=0$. We can estimate the coherence length introduced by the coupling with the in-plane magnetic field. Using the gauge $\mathbf{A}=(B_\perp z,0,0)$, the Hamiltonian is independent of $\hat{x}$ and $\hat{y}$ and the electron wave function is $e^{ik_x x}e^{ik_y y}\,\xi_n(z)$. The problem can be analytically solved in the case of a parabolic well with an associated frequency ω_0.[18] The energy levels are then given by $E_{nk_xk_y}=\hbar\omega(n+1/2)+E$, where $E=(\hbar^2/2m^*)(\Lambda k_x^2+k_y^2)$, $\Lambda=\omega_0^2/(\omega_0^2+\omega_c^2)$, and $\omega^2=\omega_0^2+\omega_c^2$, where ω_c is the cyclotron frequency. At constant energy E, the additional in-plane magnetic field modifies the x component of the wave vector: $dk_x \propto \sqrt{E}\omega_c^2/\omega_0^2$. The phase is modified by π along a closed loop of length $L_\perp \sim 2\pi\hbar\omega_0^2\omega_c^{-2}/\sqrt{2m^*E}$. By solving self-consistently the one-dimensional Poisson and Schrödinger equations, we estimate that the electron wave function of the 2DEG has an extension $\sqrt{\langle z^2\rangle}\sim 5$ nm along the z direction. This gives $\hbar\omega_0 \sim 20$ meV and $L_\perp\sim 150$ nm$(\sim L_c)$ at $B_\perp=7$ T. Thus, the LDOS fluctuations should be only weakly modified in a field $B_\perp$ of a few tesla. Second, the Dresselhauss and Bychkov-Rashba spin-orbit interactions can modify the LDOS pattern but this effect is expected to be negligible in our case. The distance L_{so} an electron travels before reversing its spin is given by $L_{\mathrm{so}}=\hbar^2(2m^*\alpha_{\mathrm{so}})^{-1}$, where α_{so} is the strength of the spin-orbit coupling. For GaAs quantum wells, the reported values of α_{so} are on the order of 5 meV·Å,[19,20] which gives $L_{\mathrm{so}}\sim 1$ μm$\gg L_c$. Finally, the field $B_\perp$ also interacts with the 2DEG via the Zeeman effect, which adds to the particle energy a quantity $\pm g\mu_B B_\perp/2$, where μ_B is the Bohr magneton. LDOS fluctuations depend on the orbital part of the Hamiltonian only. As the Zeeman term does not couple to this part, the LDOS maxima are split by the Zeeman effect as $\Delta E_{\mathrm{LDOS}}=|g|\mu_B B$.

The magnetic field also acts on the impurity. In the following, we consider only the Zeeman term which gives a change in energy: $E_I^{\pm}=\pm g_I\mu_B B/2$, where g_I is the Landé g factor of the impurity. Due to the very small current flowing, the two spin species in the 2DEG are in thermal equilibrium and have the same Fermi energy. Thus, the two onsets of tunneling V_{th}, corresponding to the alignment of ε_F with the impurity energies $E_I^{\pm}$, are separated by a voltage difference,

$$\Delta V_{\mathrm{th}}=\alpha|g_I|\mu_B B. \tag{1}$$

Let us now assume that spin is conserved during the tunneling process. Current maxima associated with LDOS maxima will be split into two peaks, corresponding to the tunneling of the spin up (down) electron to the spin up (down) level of the impurity spectrometer (see Fig. 1). The observed splitting of the current maxima depends on the relative amplitude of the spin splitting in the 2DEG and the spin splitting of the impurity spectrometer:

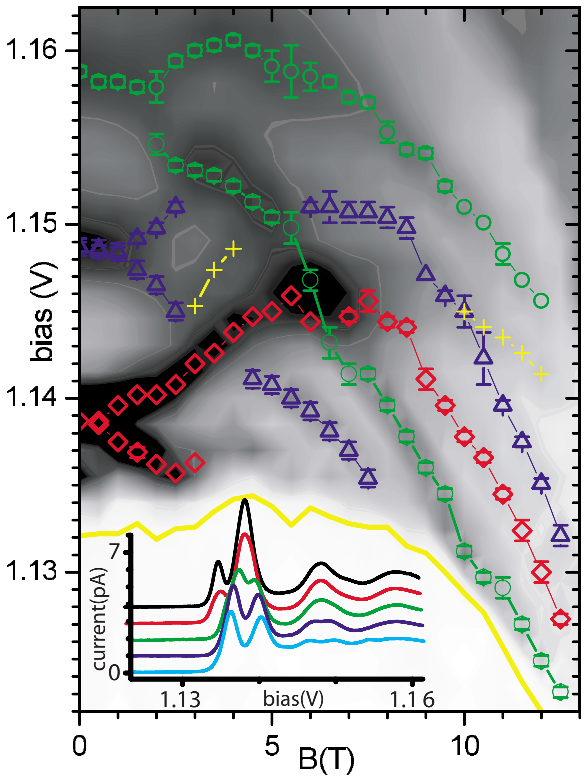

FIG. 3. (Color online) Grayscale map of the $I(V,B)$ curves obtained at $T=20$ mK with B perpendicular to the current. Dark regions correspond to high current. Open symbols report the evolution of the current peaks. The solid yellow (gray) curve corresponds to the first onset of the tunnel current. Inset: splitting of the LDOS maxima observed in the $I(V)$ curves in the range from $B=0$ (top curve) to 2 T (bottom curve); the curves of the inset have been shifted horizontally and vertically for clarity.

$$\Delta V_{\mathrm{LDOS}} = \alpha|g - g_I|\mu_B B. \qquad (2)$$

Experimentally, the two splittings ΔV_{LDOS} and ΔV_{th} can be discriminated because the current onset depends on temperature while LDOS is temperature independent.

The inset of Fig. 3 shows the evolution of the $I(V)$ curves from $B_\perp=0$ T to $B_\perp=2$ T at $T=20$ mK. The two LDOS maxima observed at $V\sim 1.14$ V and $V\sim 1.15$ V split linearly with $B_\perp$. The threshold voltage is shifted with respect to Fig. 2 because the sample was warmed up and cooled down between the two field configurations. Figure 3 shows a grayscale map of the $I(V)$ curves with larger V and B ranges, revealing the splitting of the third LDOS maximum (at $V\sim 1.16$ V for $B_\perp=0$). The positions of all LDOS maxima as a function of V and B are also indicated with open diamonds, triangles, and circles. These symbols correspond to, respectively, the first, second, and third LDOS maxima observed at $B=0$ T. Only a few extra maxima, indicated by crosses, could not be attributed. The solid yellow (gray) line corresponds to the first current onset. Its quadratic shift to lower bias at high field can be attributed to the diamagnetic term ω introduced previously. Some LDOS fluctuations cross the current onset (e.g., the lower diamond line disappears above 3 T), possibly because of the Fermi energy evolution with B.

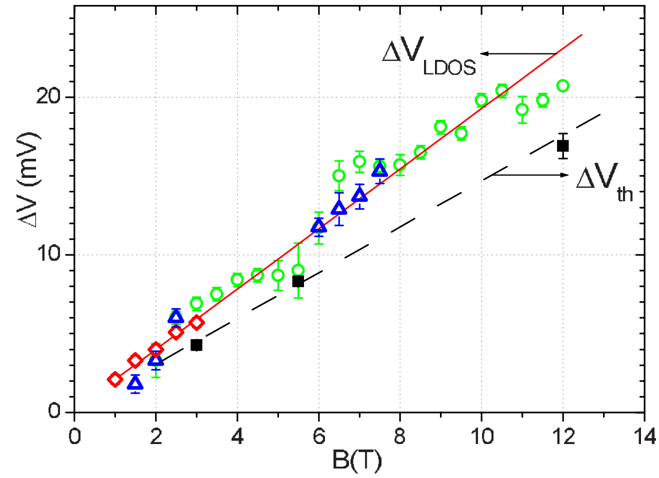

FIG. 4. (Color online) Open symbols: splitting of the current maxima associated with the LDOS. Solid symbols: splitting detected at current onsets.

A simple calculation of the Fermi energy gives $\varepsilon_F = \hbar^2 \pi n_s \Lambda^{1/2}/m^*$ and shows that ε_F decreases as $\Lambda^{1/2}$ for a constant electron concentration.

In Fig. 4, we plot the splitting extracted from the three

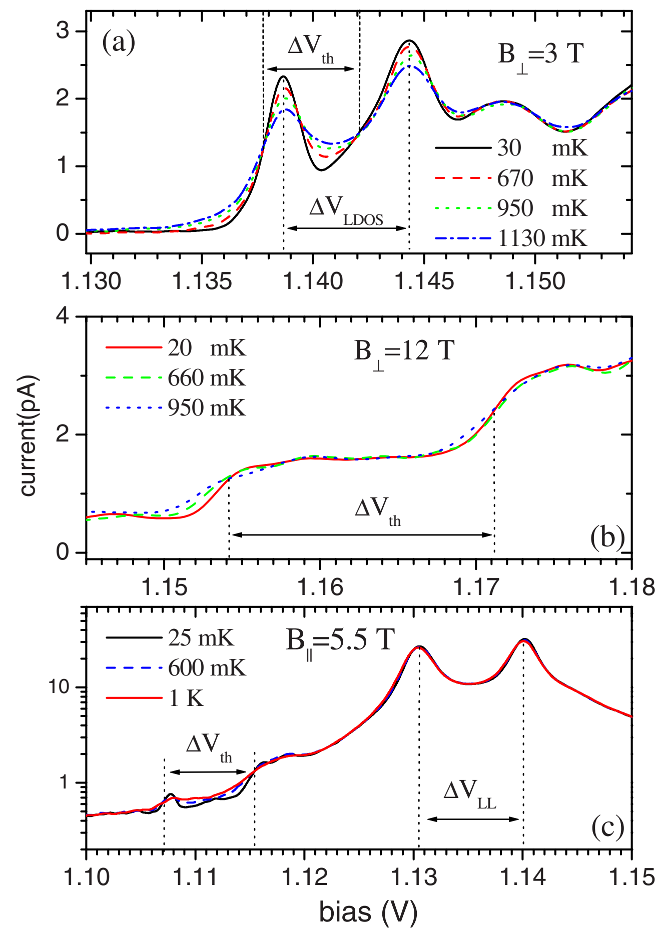

FIG. 5. (Color online) Extracted splitting at ε_F from $I(V)$ curves taken at different temperatures, at (a) $B_\perp=3$ T, (b) $B_\perp=12$ T, and (c) $B_\parallel=5.5$ T.

LDOS maxima (open symbols). All experimental points lie on the same line and a linear fit goes through the origin and gives a slope corresponding to $|g_I - g| = 2.58 \pm 0.15$.

Due to the temperature sensitivity of the current onset, the splitting of the impurity can be addressed independently.[20] Figure 5(a) shows the $I(V)$ curves at $B_\perp = 3$ T for different temperatures from which we extract $\Delta V_{\text{th}} = 4.3$ mV and $|g_I| = 1.95 \pm 0.12$. Similar temperature studies have been performed at $B_\perp = 12$ T. Unfortunately, we could not precisely resolve the splitting V_{th} for the GS of the impurity because of the current reduction due to an increasing effective barrier width (when the cyclotron radius is comparable to the barrier length[21]). However, this is possible for the first excited state where the current is larger [Fig. 5(b)]; we find $|g_I| = 1.92 \pm 0.12$. In order to check for a possible anisotropy of the g factors, additional experiments have been performed with B parallel to the current. At high field, LLs appear in the LDOS and their splitting ΔV_{LL} is easily discriminated from the splitting at ε_F. Figure 5(c) shows $I(V)$ curves at $B_\parallel = 5.5$ T, which give $\Delta V_{\text{th}} = 8.3$ mV ($g_I = 2.05 \pm 0.12$) and $\Delta V_{\text{LL}} = 9.5$ meV ($|g_I - g| = 2.34 \pm 0.14$). Therefore, within the experimental resolution, the spin splittings are isotropic. The splitting obtained from the temperature dependence, plotted in Fig. 4 (solid symbols), is aligned as indicated by the dashed line. A linear fit gives $g_I = 1.96 \pm 0.16$. This value agrees well with the theoretical value of 1.9 (Ref. 22) and with the recent experimental values.[2] The difference between the slopes of the two lines of Fig. 4 is large enough to indicate that g_I and g have opposite signs. As for GaAs the Landé g factor is negative, $g_I > 0$ and $g = -0.62 \pm 0.22$.[23] Finally, the systematic splitting of the LDOS maxima into two components (and not four), while both g and g_I are finite, indicates that electron spin is conserved in the tunneling process between the 2DEG and the donor.

To conclude, we have analyzed the LDOS fluctuations by means of the resonant tunneling through an individual impurity. Under magnetic field the spin splitting of the structures observed in the tunneling current is clearly resolved. The analysis of the splitting of the current onset and of the LDOS gives information about the magnitude of Landé g factor values for both the GaAs electron gas and the Si impurity related to the X minimum and allows us to determine the relative sign of the g factors. Our data confirm that spin is conserved in the tunneling process.

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