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Electric-field inversion asymmetry: Rashba and Stark effects for holes in resonant tunneling devices

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We report electric-field-induced modulation of the spin splitting during the charging and discharging processes of a *p*-type GaAs/AlAs double-barrier resonant-tunneling diode under an applied bias and magnetic field. In addition to the conventional Zeeman effect, we find experimental evidence of excitonic spin splitting produced by a combination of the Rashba spin-orbit interaction, the Stark effect, and the charge accumulation. The abrupt changes in the photoluminescence with the applied bias provide information about charge accumulation effects in the device.

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The effect of spin-orbit (SO) interaction in quasi-two-dimensional (Q2D) systems has attracted renewed attention in recent years. The topic has been the focus of many optical and transport investigations of spin-related phenomena in nanoscopic systems,[1–3] an area of great fundamental and technological interest.[4–7] In this Rapid Communication, we address experimental evidence of coupling between the electric field and the spin degree of freedom of carriers in resonant-tunneling devices (RTDs). Here in particular, the prevailing influence is mainly attributed to the SO and Stark effects of the hole electronic structure. These interactions are relevant to the study of the internal electric fields and the charge accumulation in the structure. The simultaneous investigation of optical and transport properties at high magnetic and electric parallel fields has permitted a thorough characterization of the main processes involved in the system response. The novelty of this result consists of the optical detection of the electric-field modulation of the effective spin splitting beyond the Zeeman effect and its unambiguous correlation to the transport mechanism, which is responsible for the charge buildup in the RTD.

This study is carried out on a symmetric *p*-*i*-*p* GaAs/AlAs RTD, with 4.2 nm (5.1 nm) well (barrier) width, that has been previously used to characterize the hole space charge buildup and resonant effects in a magnetic field.[8–11] A 400-μm-diameter mesa diode with a metallic AuGe annular top contact was used to allow optical access. The structure was mounted in a superconducting magnet and the emission spectra were recorded using a double spectrometer coupled to a charge-coupled device system with polarizer optics to select left (right) $\sigma^{+(-)}$ configurations. As the bias approaches a resonant condition, the carrier density inside the quantum well (QW) increases and then abruptly decreases when the resonance is traversed, resulting in a negative differential resistance region. When light from an Ar^+ laser is focused at the sample, minority electrons are created.[8] The photogenerated electrons tunnel into the QW layer and can thus recombine with the injected holes into the QW or tunnel out of the well, resulting in a photocurrent. These processes are represented schematically in Fig. 1.

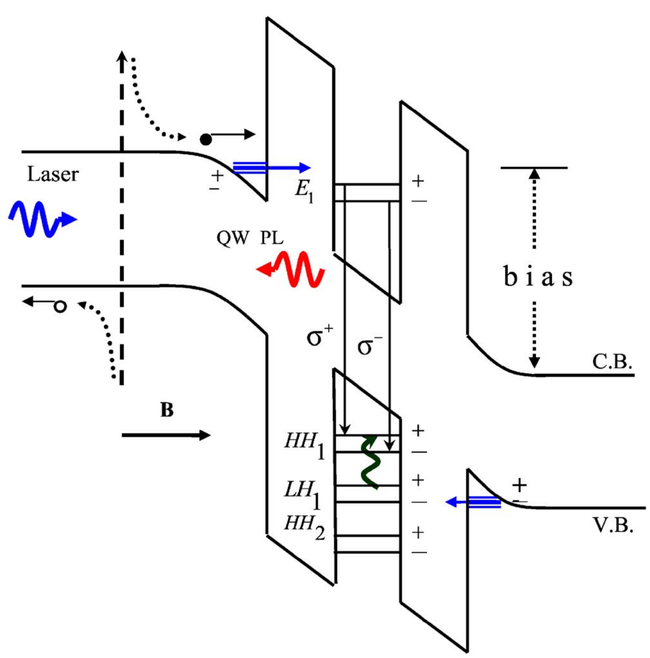

FIG. 1. (Color online) Schematic diagrams for tunneling and recombination processes in the GaAs-AlAs RTD under illumination. In this configuration, the top mesa contact is biased. Majority holes are injected into the QW from the right. Photocreated minority electrons enter the QW from the left.

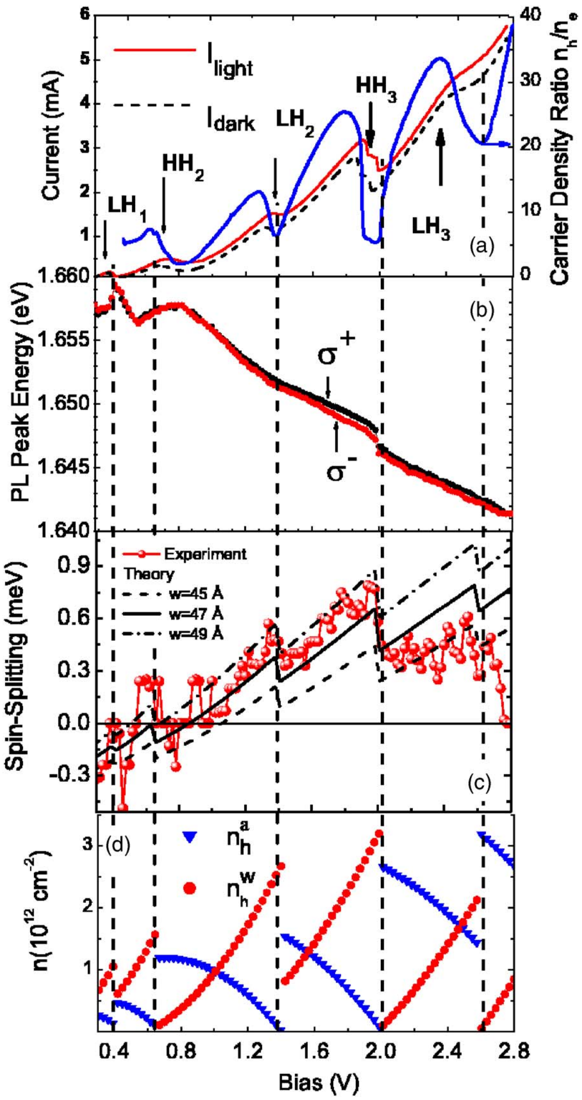

FIG. 2. (Color online) (a) The *I-V* characteristics with (I_{light}) and without (I_{dark}) illumination. The carrier density ratio is calculated through $n_h/n_e = 2I_{dark}(V)/[I_{light}(V) - I_{dark}(V)]$. (b) Energy peak positions of $\sigma^{\pm}$ PL spectra as a function of bias at $B=15$ T. (c) Measured spin splitting of excitonic recombinations at $B=15$ T, for increasing bias (represented by circles) and calculated spin-splitting energy of excitonic recombination in GaAs QWs of various widths (represented by dashed, solid, and dash-dotted curves). Vertical dashed lines show the critical voltages where abrupt changes in the properties occur for $B=15$ T. (d) 2D hole density fluctuation in the accumulation (n_h^a) and QW layers (n_h^w) used in the calculations.

The *I-V* characteristics, shown in Fig. 2(a), display a series of peaks attributed to resonances between the fundamental hole state at the accumulation layer and the various QW hole subbands (I_{dark}) identified by labels in Fig. 2(a). With illumination, the current increases due to the injection of minority electrons (I_{light}). Under this condition, one observe the emergence of photoluminescence (PL) emission from the fundamental QW subbands, as shown schematically in Fig. 1. PL spectra were recorded for σ^+ and σ^- circular polarizations as a function of the bias voltage. The energy of the PL bands with distinct polarizations as well as the resulting spin splitting as a function of bias voltage are shown in Figs. 2(b) and 2(c), respectively.

Assuming a similar escape rate for electrons and holes out of the QW, the ratio between the majority (n_h^w) and minority (n_e^w) carrier densities inside the QW should be given approximately by the ratio between the current generated solely by holes and by electrons. This ratio is also shown in Fig. 2(a) as a function of bias for our highest laser excitation intensity condition. Note that the density of holes under illumination is always much larger than the density of electrons (minority carriers). The ratio n_h^w/n_e^w increases smoothly during the charge buildup process, as the bias is swept between two hole-resonant voltages, and shows abrupt variations only around the peaks of the resonances. The abrupt variations are partially attributed to an abrupt decrease of n_h when a hole resonance voltage is crossed, and partially to a small shift of the resonance voltage with illumination due to the consequent variation of charge distribution along the structure. In our model, we will thus consider $n_h^w \gg n_e^w$, with n_h^w increasing smoothly between resonances and with abrupt reductions at those voltages.

As the bias (electric field) increases, the energies of both the σ^+ and σ^- PL peaks show an overall redshift as expected by the quantum Stark effect, but sharp discontinuities also appear at the hole-resonant voltages for both spin-selected emissions. Abrupt variations of the PL energy from RTD devices have been attributed to changes in the QW charge density near the critical voltages, thus inducing changes on the built-in electric field.[15] A detailed analysis of the PL peak energies is, however, rather complex. We have to consider that the PL emission from the 2D-hole-rich gas in the QW must arise from the recombination of either positive trions (X^+) or neutral excitons (X^0).[12,13] Therefore, an increase in the carrier density in the QW leads not only to a Stark shift, which depends on the resulting electric field from the charge distribution along the structure, but also to the variation of binding energy of the excitonic complexes in the presence of the 2D gas.[14] Precise calculation of those competing effects for our structure is a very complex task. On the other hand, the spin-splitting energy shown in Fig. 2(c) is not affected by excitonic corrections. We will therefore restrict our model to describe this experimental result.

The discontinuities observed at the PL peak energies around the resonant voltages are even more evident in the total spin-splitting energy vs bias voltage displayed in Fig. 2(c). Note that the splitting energy shows a continuously increasing trend as the bias voltage is increased between two resonant voltages. Besides the usual Zeeman effect, two other SO interactions affect the effective spin splitting of the QW energy levels: (i) the bulk inversion asymmetry or Dresselhaus term for zinc-blende structures only, and (ii) the structure inversion asymmetry or Rashba term, under an applied electric field.[16,17] Both contributions depend on the material SO parameters and their effects can be enhanced by the presence of a magnetic field.[16] Under our experimental conditions, these two terms may be comparable; however, only the Rashba contribution is directly proportional to the bias voltage. Since we are mainly concerned with the variation of the spin splitting with the voltage applied to the structure, we consider here only the Rashba term. This approximation does not affect the qualitative results of our analysis but leads to an effective charge density that includes a constant which may not be negligible, an effect due to the Dresselhaus term.

The model used to describe the complex behavior of our device is based on the states of a square QW potential with infinite barriers. We consider that the carriers on those states are subjected to a bias-dependent uniform electric field resulting from the charge distribution along the structure. The coupling between this electric field and the spin degree of freedom is introduced via the Rashba SO Hamiltonian for electrons[16,17] and holes.[18] The Luttinger Hamiltonian provides an accurate description of the valence band admixture and allows us to treat the magnetic (B) and electric (F) fields as well as the Rashba term in the same framework. The full Hamiltonian $H^{cond(val)}=H^L \pm I_{2j+1}eFz+H^{SO}$ is decomposed into three terms: (i) H^L describes the dynamics of the Landau quantization and the Zeeman effect; (ii) $I_{2j+1}eFz$ contains the Stark-shift-related terms that produce the inversion asymmetry induced by the electric field (F), where I_{2j+1} is the $(2j+1)$-rank unity matrix; and (iii) H^{SO} is the Rashba term that couples the dynamical linear momentum with the spin degree of freedom. The Rashba term is treated in the $(2j+1)$-rank representation of the total momentum with $j=1/2$ for electrons and $j=3/2$ for holes[18] as

$$H_{\gamma}^{SO} = \alpha_{\gamma}\frac{\sqrt{2}F}{\lambda_c} i(aJ_{+} - a^{\dagger}J_{-}), \tag{1}$$

where $\alpha_{cond(val)}$ is the Rashba SO parameter for the conduction (valence) band, λ_c is the magnetic cyclotron radius, and $J_{\pm}=1/2(J_x \pm J_y)$, where J_i is the 4×4 (2×2) angular momentum matrix for holes (electrons). One advantage of this SO representation is that it allows a wave-function expansion with a well-established sequence of components. The basis set combines the band edge periodic Bloch functions in the total momentum representation $|s\uparrow\downarrow\rangle$, $|hh\uparrow\downarrow\rangle$, $|lh\uparrow\downarrow\rangle$; the vertical eigenstates $A_{2k-1}(z)$ even and $A_{2k}(z)$ odd parity for $k=1,2,\ldots$; and the lateral Landau states $|N\rangle$. The eigenfunctions $\Phi_{c(v)}$ for the conduction (valence) band states have the general form

$$\Phi_c = \begin{bmatrix} A_1^c|N\rangle|s\uparrow\rangle \\ A_1^c|N+1\rangle|s\downarrow\rangle \\ A_2^c|N\rangle|s\uparrow\rangle \\ A_2^c|N+1\rangle|s\downarrow\rangle \\ A_3^c\cdots \end{bmatrix}, \quad \Phi_v = \begin{bmatrix} A_1^v|N-2\rangle|hh\uparrow\rangle \\ A_1^v|N-1\rangle|lh\uparrow\rangle \\ A_1^v|N\rangle|lh\downarrow\rangle \\ A_1^v|N+1\rangle|hh\downarrow\rangle \\ A_2^v|N-2\rangle|hh\uparrow\rangle \\ A_2^v|N-1\rangle|lh\uparrow\rangle \\ A_2^v|N\rangle|lh\downarrow\rangle \\ A_2^v|N+1\rangle|lh\downarrow\rangle \\ A_3^v\cdots \end{bmatrix}, \tag{2}$$

where $N=-1,0,1,2,\ldots$ is the effective Landau index.[19] The sequence of periodic valence Bloch states in the components is determined by the sequence chosen to write the Luttinger Hamiltonian. These vector states have, in principle, infinite dimension since the index k, used to enumerate the functions A_{2k-1} and A_{2k}, runs over all positive integer numbers.

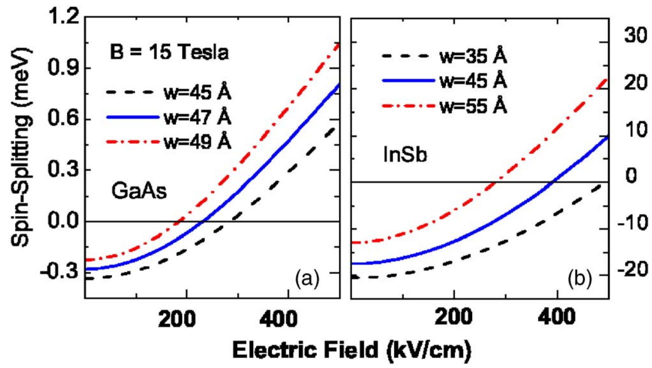

FIG. 3. (Color online) (a), (b) Calculated spin-splitting energy of excitonic recombination in identical QW's of different III-V compounds, as a function of the electric field for various QW widths.

Figures 3(a) and 3(b) show the calculated spin-splitting energy for the excitonic recombination in GaAs and InSb QWs as a function of the uniform electric field in the well. The effective spin splitting for holes and electrons can thus be tuned by the external field F. The result reflects the strong admixture of states generated by the combination of Rashba-SO and Stark effects, in particular, for the valence band. Note that the strength of this modulation can be enhanced for materials with larger SO parameters (such as in InSb) as shown in Fig. 3(b). Interestingly, this effect can be optically observed only in the presence of the external magnetic field, since the Rashba spin splitting goes to zero for those carriers with in-plane wave vectors close to zero that are involved in the PL emission without magnetic field.

A precise estimation of the electric field experienced by the carriers at the QW for a given bias voltage can only be obtained by a self-consistent calculation considering all the charges in the structure. A simple and satisfactory relationship between the averaged electric field at the QW, F, and the applied bias voltage V can, however, be obtained by considering that hole gases formed at the QW and the accumulation layer can be described by ideal 2D charge distributions. We thus obtain[8] $F=\frac{e}{\epsilon_0\epsilon}(n_h^a+n_h^w)$ and

$$V = \frac{e}{\epsilon_0\epsilon}\left(\frac{(n_h^a+n_h^w)^2}{2N_A} + n_h^a L_a + n_h^w L_w\right), \tag{3}$$

where ϵ is the static dielectric constant for GaAs, $L_a=(2b+w+u+\lambda_1)$, $L_w=(b+u+\lambda_2)$, n_h^a and n_h^w are the 2D hole densities at the accumulation and the QW layers; $w=4.2$ nm, the QW width; $b=5.1$ nm, the barrier thickness; $u=5.1$ nm, the spacer layer width; $N_A=5\times 10^{17}$ cm^{-3} is the nominal 3D density of ionized acceptors in the depletion layer; λ_1 is the distance of the QW hole gas from the barrier; and λ_2 is the distance of the accumulation hole gas from the emitter barrier. We have used the nominal values for the layer thicknesses for the sample used in our study. λ_1 was considered much smaller than w and λ_2 was estimated from the Fang-Howard wave function (Ref. 11 in Ref. 8). It is reasonable to assume that the carriers inside the QW experience the full electric field generated by the QW hole gas.

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There is thus a relation between the bias voltage V and the electric field in the QW, F, which is related to the spin-splitting energy by our theoretical model. This relation depends on only two adjustable parameters, the 2D densities n_h^w and n_h^a. The 2D densities used to describe the experimental results from Fig. 2(c) are displayed in Fig. 2(d). All the other parameters for GaAs used in this simulation, such as effective masses and Luttinger and Rashba parameters, were taken from the literature.

The resulting hole densities increase smoothly between resonances and exhibit abrupt changes as the bias is swept through the resonant tunneling channels associated with the valence band, as expected. The spin-splitting energy is well described by the nominal values used in our simulation. As shown in Fig. 2(d), the experimental error of our results is comparable with small uncertainties in device parameters, e.g., the precise width of the QW or spacer layers. The resulting hole densities are within the expected range for this kind of structure and only slightly smaller than that deduced from transport measurements.[8] The small discrepancy may be due to our neglect of the Dresselhaus term. The deduced hole densities may thus be considered as valid, but do not affect the qualitative description of our results.

In summary, we have observed a strong correlation between the optically measured spin-splitting energy and the resonant tunneling bias voltages from the *I-V* characteristics. This result in itself is clear evidence that the spin splitting of the RTD structure can be modulated through spin-orbit effects. The simulation of the experimental results using a simple model provide confirmation of our analysis. The spin splitting induced by the combined effect of interband interactions, the Rashba and the Zeeman terms, can be viewed as a sensitive probe of the relationship between the internal QW field F and the continuously varying bias voltage V. Also, the modulation of the spin-splitting energy by an external bias could have potential for device applications. Our results reveal clearly the processes whereby the spin degree of freedom can be effectively coupled to the electric field in nonmagnetic tunneling devices.[20]

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