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Polarization resolved luminescence in asymmetric *n*-type GaAs/AlGaAs resonant tunneling diodes

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We have investigated the polarized emission from a *n*-type GaAs/AlGaAs resonant tunneling diode under magnetic field. The GaAs contact layer emission shows a large constant negative circular polarization. A similar result is observed for the quantum well, but only when electrons are injected from the substrate, while for inverted biases, the polarization tends to become positive for small voltages and large laser excitation intensities. We believe that the quantum well polarization may be associated to the partial thermalization of minority carriers on the well subbands and is thus critically dependent on the bias-controlled density of carriers accumulated in the well. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2908867]

The exploitation of the spin degree of freedom in addition to the charge of carriers, is a major aspiration for semiconductor device development. Some key points for this technology are the generation, coherent transport, and manipulation of spin-selected carriers. Spin injection into semiconductor structures has been studied on several devices resulting in significant progress in the last few years.[1–9] The possibility of using resonant tunneling diodes (RTDs) for spin filtering was first demonstrated using semimagnetic II-VI materials.[10,11] More recently, spin selection was observed in III-V nonmagnetic structures.[12,13] Both approaches are based on the Zeeman splitting of the levels involved in tunneling and thus depend on an external magnetic field. In this letter, we present the investigation of the polarized resolved photoluminescence (PL) from an asymmetric *n*-type RTD with a GaAs quantum well (QW) and two AlGaAs barriers with different widths.

Our structure was grown by molecular beam epitaxy on a n^+ (001) GaAs substrate and its active region consists of 2 μm *n*-GaAs (1×10^{18} cm^{-3}), 509 Å *n*-GaAs (1×10^{17} cm^{-3}), 509 Å *n*-GaAs (1×10^{16} cm^{-3}), 34 Å undoped GaAs spacer, 71 Å $Al_{0.4}Ga_{0.6}As$ barrier, 59 Å GaAs QW, 113 Å $Al_{0.4}Ga_{0.6}As$ barrier, 34 Å GaAs spacer, 509 Å *n*-GaAs (1×10^{16} cm^{-3}), 509 Å *n*-GaAs (1×10^{17} cm^{-3}), and 0.51 μm *n*-GaAs (1×10^{18} cm^{-3}). Circular mesas of 200 μm diameter were processed with annular AuGe contacts to allow optical measurements. PL measurements were performed at 2 K at magnetic fields up to 15 T. A linearly polarized Ar$^+$ laser was used for optical excitation, and σ^+ and σ^- polarized emissions were selected by using appropriate optics. Therefore, the photogenerated carriers in our structure should not present any preferential spin polarization.

Figure 1(a) shows a diagram of our structure under laser excitation. Due to the actual dimensions of the mesa and the laser beam, light reaches both the top and the back contact layers at the substrate side. Figure 1(b) shows a schematic band diagram of our structure for positive and negative bias voltages, under light excitation and a magnetic field applied parallel to the tunnel current. For $V>0$, photogenerated holes (minority carriers) from the top contact can tunnel through the structure and recombine in the QW and also in the opposite contact layers with tunneling electrons from the n^+ substrate side (majority carriers). Under this condition, the second barrier for tunneling electrons is larger than the first one, which favors the accumulation of electrons in the QW. For $V<0$, only those photo-generated holes generated at the substrate side can tunnel through the double barrier and thus recombine with electrons from the top contact. In this case, the second barrier for tunneling electrons is the thinnest one and we expect a reduced accumulation of electrons in the QW. On the other hand, the asymmetry of the barriers should favor the accumulation of holes in the QW in this configuration. We believe that this point can drastically affect the bias dependence of the circular polarization in the QW, as we will discuss in the following.

We have not observed any PL emission from the QW at zero bias voltage, which indicates that the generation of carriers inside the QW is negligible under our experimental conditions. Typical PL spectra at 15 T for ±0.6 V are shown in Fig. 2. We observe two emission regions. The higher energy band at ~1.60 eV is associated with the fundamental QW transition, whereas the emission at ~1.52 eV is associated with the GaAs contact layers, including donor-related emissions from both the n^+ GaAs substrate (broad emission) and *n*-doped GaAs layers (narrow line at ~1.523 eV), and also the space-indirect recombination between tunneling holes and electrons localized at the two-dimensional electron gas (2DEG) formed at the accumulation layer (~1.521 eV). The 2DEG space-indirect emission is strongly bias dependent, as recently observed in *p-i-n* and *n-i-n* RTDs.[13,14] The emission band from the n^+ GaAs substrate used in the growth of our structure is also presented in Fig. 2. The n^+ GaAs substrate presents a large negative degree of circular polarization (~55%), which is attributed to the spin splitting of the bulk GaAs bands. The resulting polarization must be controlled by the *g*-factor of the minority carriers (holes) since the large density of electrons should result in a negligible unbalance of

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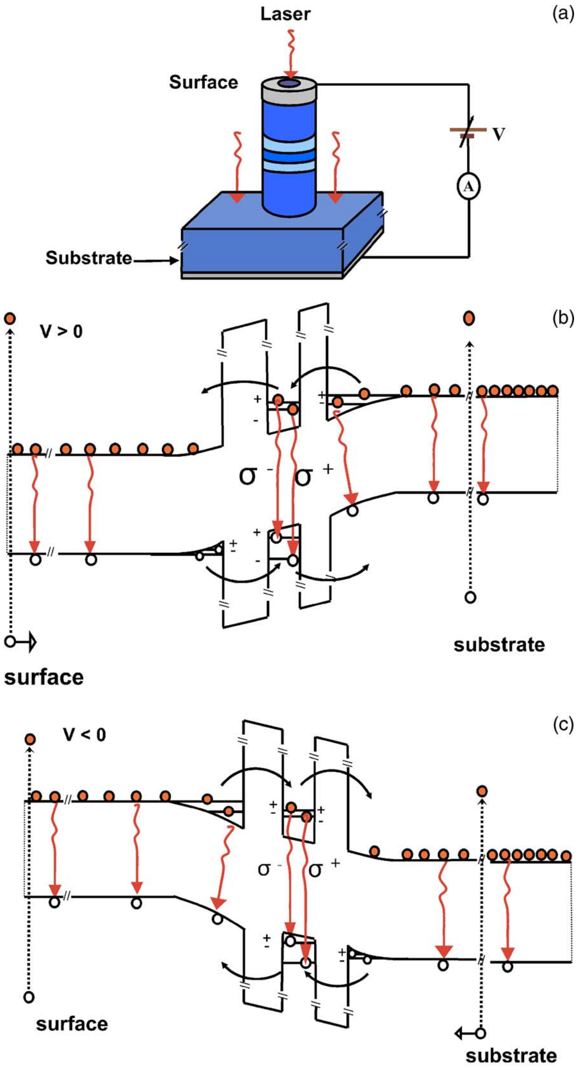

FIG. 1. (Color online) (a) RTD structure. (b) Schematic band diagram of our structure under forward and reverse voltages.

electrons with distinct spin values. The calculation of the circular polarization depends on parameters that have a relatively large uncertainty, such as density of the photocreated holes along the structure, but a simple estimation based on the spin splitting of conduction and valence bands and carrier statistics is in reasonable agreement with the measured value.

The current-voltage (*IV*) characteristics at 0 and 15 T in the dark and under two different light excitation intensities ($I_1 \sim 9.5$ W/cm^2 and $I_2 \sim 13.3$ W/cm^2) are presented in the upper panels of Fig. 3, including positive and negative bias voltages. We observe two resonant peaks associated with the first (e_1) and second (e_2) electron resonances followed by negative differential resistance regions. The resonant voltages are different for positive (0.98 and 1.27 V) and negative biases (−0.28 and −1.31 V) due to distinct charge accumulation conditions, as discussed before. Under magnetic field, some structures are observed in the *IV* curves associated with tunneling through the Landau levels formed in the accumulation layer and QW. We remark that for low voltages, the photocurrent due to photogenerated holes is markedly larger than the electron current in the dark, which indicates that the holes actually become the effective majority carrier inside the QW under this condition.

The lower panel of Fig. 3 presents the degree of circular polarization from the contact layer and the QW emissions as

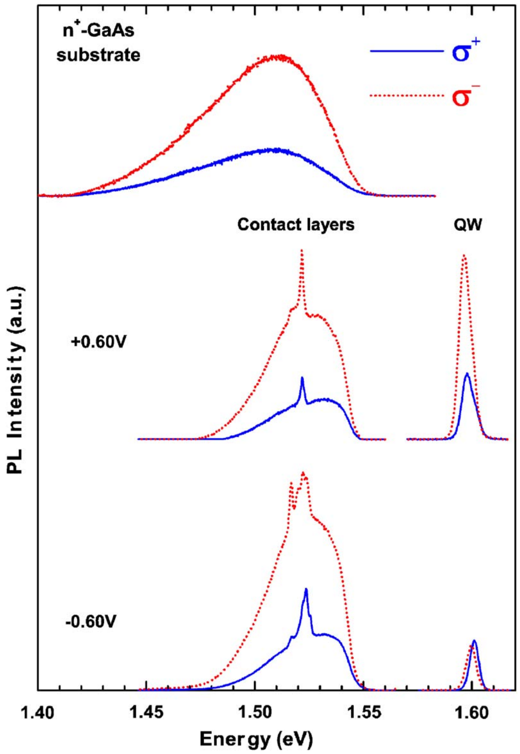

FIG. 2. (Color online) Typical σ^+ and σ^- PL spectra for an n^+ bulk GaAs substrate sample and from the RTD under a ±0.6 V bias voltage and 15 T.

function of the bias voltage. In the case of the contact layer, the polarization degree was calculated by integrating the whole emission band, which is mainly dominated by the recombination from the GaAs substrate, but it also includes the emission from the *n*-doped layers and the *h*-2DEG transition. The polarization from the integrated contact emission is $\sim -50\%$ for all bias voltages. For $V > 0$, the QW emission also presents a large negative polarization degree, which is comparable to the contact layer polarization and is mainly independent of the bias voltage and laser intensity. In contrast, for $V < 0$, the QW emission presents a circular polarization that depends on the bias voltage, varying from positive ($\sim +10\%$) to negative ($\sim -40\%$) values. In this case, the QW polarization degree is also sensitive to the laser excitation intensity. The spin splitting obtained from the QW emission bands is of the order of 1 meV. Only a small variation of this value as a function of the bias voltage is observed, which we believe is a result of a mixture of two distinct QW emission bands related, respectively, to the exciton and trion recombination. The relative intensity of those bands varies with the applied bias and should have slightly different spin-splitting energies, but since they cannot be resolved, it results on the observed spin-splitting variation. For $V < 0$, the QW spin splitting varies from ~ 1.5 to ~ 0.8 meV as we increase the voltage from 0 to 1.8 V. We remark, however, that within this bias voltage range the polarization of the QW emission does significantly change and it even presents a sign inversion. For $V > 0$, the spin splitting varies within 1.3–1.7 meV for the same bias variation and the polarization mainly remains constant. Therefore, the observed circular polarization of the QW emission cannot be simply attributed to the QW spin-splitting variation.

As discussed before, the minority carriers tend to define the effective polarization of an optical recombination. We have to remark, however, that the quasibound states of the

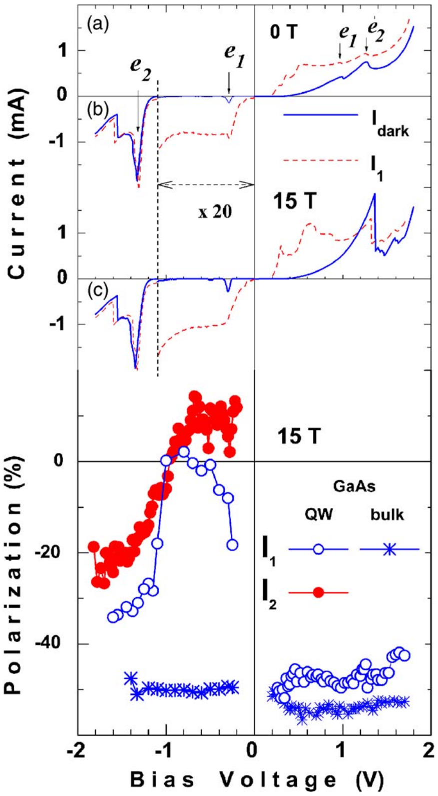

FIG. 3. (Color online) Bias voltage dependence of (a) current in the dark and under light excitation for two laser intensities and (b) current in the dark and under light excitation under magnetic field 15 T parallel to the tunnel current. (c) Circular polarization degree from the GaAs contact layers and QW emissions under forward and reverse biases.

RTD QW should not follow a simple thermal equilibrium statistics. The final polarization of the QW emission should thus depend on the spin polarization of the injected carriers, and also on the density of the electron and holes in the well and the QW spin splitting, and in a rather complex way. We also point out that the density of carriers in the QW is voltage controlled and also depends on the asymmetry of our structure.

For large voltages, when the density of electrons in the well becomes clearly dominant, both effects discussed above should induce a negative circular polarization of the QW emission, as observed. On the other hand, for low voltages (<1 V), the photogenerated holes become the major contribution for the tunneling current. The hole density inside the QW can thus become comparable and even larger than the electron density. This effect should be strongly reinforced for negative bias, since in this configuration, the barrier's asymmetry favor the accumulation of holes and hamper the accumulation of electrons at the QW, as discussed before. As the density of holes becomes larger than the density of electrons, the occupation of the spin-split hole levels should play a more significant role on the QW polarization. Since the hole g-factor from our GaAs QW should have a sign opposite to that of the electron,[15] this may result in a sign inversion of the QW polarization emission, as observed. This tendency becomes stronger as we increase the laser intensity, in agreement with the increasing density of photogenerated holes. This is also in qualitative agreement with the previous results in p-type RTD structures[12,13] where the QW circular polarization is positive due to the majority of holes in the structure, except for those bias voltages where the photogenerated electrons resonantly tunnel into the QW, when the polarization became negative. For positive low voltages, photogenerated holes also become the major contribution for the tunneling current but no sign inversion is observed in the polarization degree. This behavior is probably due to the barrier asymmetry that favors the accumulation of electrons in the QW under positive bias.

In conclusion, we have observed an interesting behavior of the degree of circular polarization from the QW emission in our asymmetric n-i-n RTD structure under 15 T. For positive bias, the polarization shows a rather large constant negative value. For negative bias, the polarization depends on the applied voltage and the laser excitation intensity, and tends to become positive for small voltages and large excitation intensities. We attribute our experimental results to the thermal occupation of the Zeeman-split levels by the minority carriers. The occupation of the spin-split contact levels results in the large negative polarization of the bulk GaAs emission and also affects the polarization of the QW emission, as it selects the dominant spin of the holes tunneling into the well. The occupation of the spin-split QW levels should also contribute to the polarization of the QW emission, even though the QW should not follow an equilibrium distribution. A main point is that this effect should be strongly affected by the large variation of the density of electrons and holes in the QW as a function of the bias voltage, which can even invert the minority carrier character in the QW. The observed control of the QW emission polarization by the applied bias voltage may be explored to design devices for spintronic applications.

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