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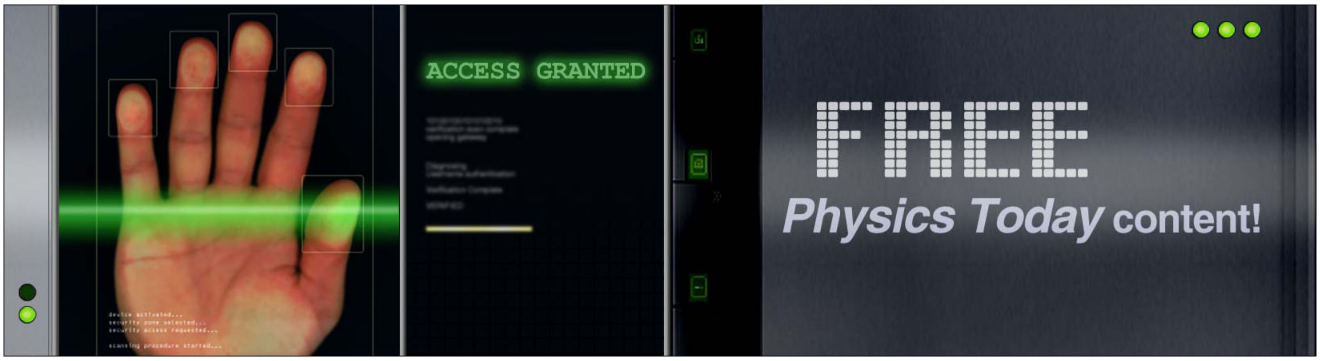

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Light controlled spin polarization in asymmetric *n*-type resonant tunneling diode

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The authors have observed a strong dependence of the circular polarization degree from the quantum well emission in an asymmetric *n*-type GaAs/AlAs/AlGaAs resonant tunneling diode on both the laser excitation intensity and the applied bias voltage. The sign of the circular polarization can be reversed by increasing the light excitation intensity when the structure is biased with voltages slightly larger than the first electron resonance. The variation of polarization is associated with a large density of photogenerated holes accumulated in the quantum well, which is enhanced due to the asymmetry of the structure. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2772662]

Recently, several experiments have demonstrated spin injection into semiconductor structures.[1–9] For device applications, it would be desirable that the spin character of the injected carriers could be controlled by external parameters such as the bias voltage. The possibility of using resonant tunneling diodes (RTDs) for spin filtering was demonstrated by using semimagnetic II–VI materials.[10,11] More recently, spin selection was observed in III–V non–magnetic 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 have investigated the polarized-resolved photoluminescence from a nonmagnetic *n*-type RTD with a GaAs quantum well (QW) and AlGaAs/AlAs asymmetric barriers, which favors a preferential accumulation of a given carrier depending on the bias sign.

Our structure was grown by molecular beam epitaxy on a n^+ GaAs substrate and its active region consists of 2 μm *n*-GaAs (2×10^{18} cm^{-3}), 0.1 μm *n*-GaAs (1×10^{17} cm^{-3}), 51 Å undoped GaAs spacer, 40 Å AlAs barrier, 50.9 Å GaAs QW, 42 Å $Al_{0.4}Ga_{0.6}As$ barrier, 51 Å GaAs spacer, 0.1 μm *n*-GaAs (1×10^{17} cm^{-3}), and 0.51 μm *n*-GaAs (1×10^{18} cm^{-3}). Circular mesas (400 μm diameter) were processed with annular AuGe contacts to allow optical measurements. Photoluminescence (PL) measurements were performed at 2 K using a Si charge coupled device system in magnetic fields up to 15 T. An Ar laser was used for optical excitation and the σ^+ and σ^- polarized emissions were selected using appropriate optics. The laser excitation is linearly polarized. Therefore, the photogenerated carriers should not present a preferential spin polarization.

Figure 1(a) shows a schematic band diagram of our structure under a positive bias voltage, light excitation, and a magnetic field parallel to the tunnel current. Under applied bias, photogenerated holes (minority carriers) can tunnel through the structure and recombine with tunneling electrons (majority carriers) at the QW and the contact layers. No PL emission from the QW is detected at zero bias, indicating that the generation of carriers inside the QW is negligible. A typical PL spectrum at 15 T and 0.6 V bias is shown in Fig. 1(b). We have observed two emission regions. The higher energy emission (~1.637 eV) is attributed to the fundamental QW transition, whereas the emission around 1.52 eV is attributed to recombination in the GaAs contact layers, including donor-related emissions from the n^+ substrate (broad emission) and the *n*-doped GaAs layers (narrow line at ~1.523 eV), and also the space-indirect recombination between free holes and electrons localized at the two-dimensional electron gas formed at the accumulation layer (~1.521 eV) [see inset in Fig. 1(b)]. The last transition, usually labeled *h*- two-dimensional electron gas (2DEG), was recently observed in a *p*-*i*-*n* RTD.[13] It presents a redshift with increasing bias which is consistent with its attributed origin. The QW emission bands at 15 T for several bias voltages are presented in Fig. 1(c). We clearly observe that the relative intensities from σ^+ and σ^- QW emission bands vary with the applied bias voltage.

The *IV* characteristics at 15 T in the dark and under two light excitation intensities ($I_0\sim9.5$ W/cm^2 and $5I_0$) are presented in Fig. 2(a). We observe a resonant peak at ~0.4 V associated to the first electron resonance (e_1) followed by a negative differential resistance (RDN) region. Under low excitation intensity (I_0), the *IV* curve does not change significantly and only shows a small shift to lower voltages, which can be associated to the photogenerated holes that tend to compensate the well known screening effect due to tunneling electrons. Under stronger light excitation ($5I_0$), the shift to lower voltages is accompanied by the appearance of a shoulder around 0.2 V, which is attributed to the first heavy-hole resonance (hh1) and by a strong increase of current after the RND region. We remark that for the high excitation condition, the illumination has a strong effect for bias values be-

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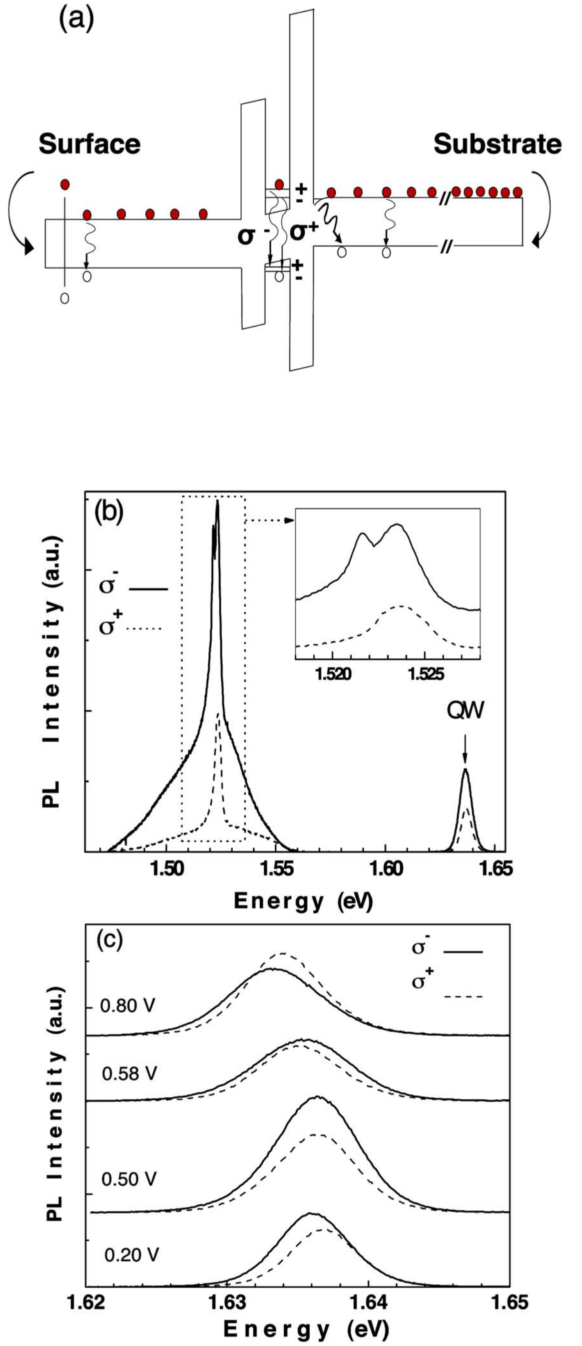

FIG. 1. (Color online) (a) Schematic band diagram of our structure under a positive bias voltage; (b) σ^{+} and σ^{-} PL spectra under a 0.6 V bias voltage and 15 T. The inset shows a detail of the low energy emission from the GaAs contact layers; (c) typical QW emission for several applied bias under 15 T.

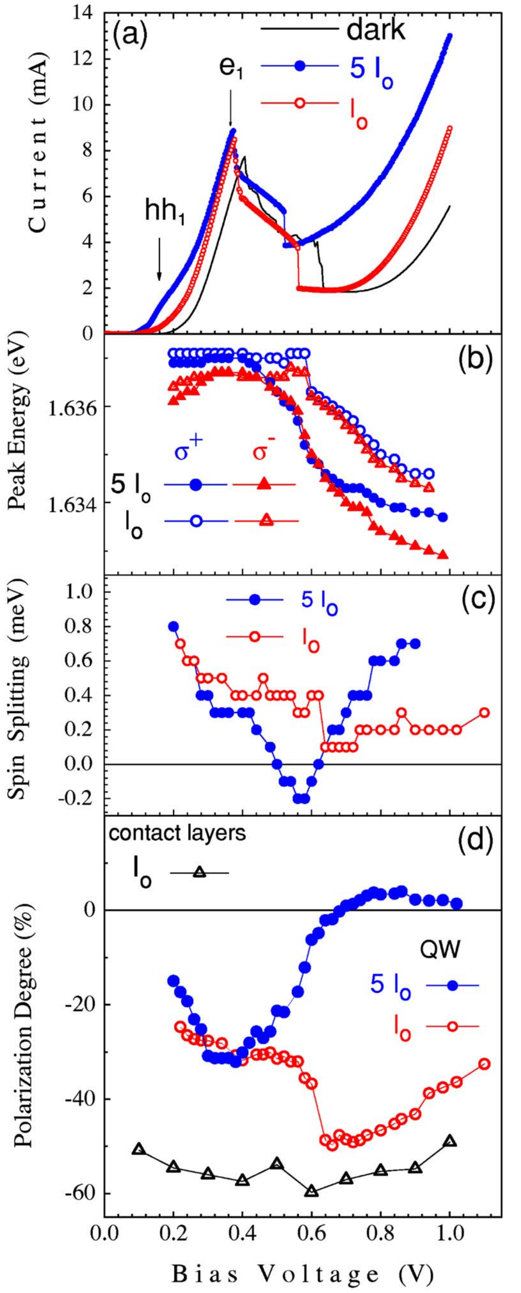

FIG. 2. (Color online) Bias voltage dependence of (a) current in the dark and under light excitation for two laser intensities; (b) Peak energies from σ^{+} and σ^{-} QW emission bands; (c) QW spin-splitting energy; and (d) circular-polarization degree from the GaAs contact layers and QW emissions.

low 0.25 V and above 0.60 V, which can even result in an inverted situation where the photogenerated holes become the majority carriers as the increase of current due to the holes becomes larger than the electron current in the dark.

Figure 2(b) presents the peak energies from the σ^{+} and σ^{-} QW emission bands versus bias voltage at 15 T. The energies show an overall redshift with increasing bias due to the Stark effect. During the e_1 resonant condition the QW levels are, however, pinned by the large density of electrons accumulated in the QW, so that the peak energies remain mainly constant. We have also observed that for the voltages where the *IV* is more strongly affected by the excitation light, the peak energies change with excitation intensity, including the RDN bias range. Therefore, only for voltages between 0.25 and 0.40 V the number of electrons in the QW largely exceeds the number of photogenerated holes and the effect of light is negligible even under high excitation conditions. The effect of the photogenerated holes in our structure is reinforced by the fact that the second barrier for holes is higher than the first one, which increases the probability of hole accumulation into the QW, while for electrons the second barrier height is lower than the first one, which acts in the opposite way, reducing the electron accumulation in the QW. This significant accumulation of holes into the QW should alter the band profile of the structure and thus, change the QW transition energies, as observed.

The QW emission from RTD structures usually includes neutral and charged excitons (trions) transitions depending on the applied voltage and the resulting charge accumulation in the QW.[14,15] However, we cannot resolve those transitions since their energy separation is smaller than our PL linewidth. Figure 2(c) presents the Zeeman spin-splitting energy from the QW emission as a function of the applied bias for low and high excitation conditions. The splitting energy varies between −0.2 and 0.8 meV, which is compatible with the individual splitting energies of the order of ~0 and ~1 meV observed, respectively, for the exciton and the trions at 15 T in similar structures.[16,17] Furthermore, the spin splitting can also be affected by the Rashba effect associated to the local electric field resulting from the applied bias and from the asymmetrical geometry of our structure. Therefore, we cannot extract any quantitative information from these data. On the other hand, it is important to point out that the resulting degree of circular polarization of the QW emission does not follow the Zeeman splitting dependence on bias, as we will show below.

The degree of circular polarization from the contact layer and the QW are presented in Fig. 2(d). In the case of the contact layer, the polarization degree was calculated by integrating the whole emission band including the recombination from the GaAs substrate, the *n*-doped layers, and the *h*-2DEG transition. Both the *h*-2DEG transition and the broad emission assigned to the n^+ substrate present a large degree of negative circular polarization, as observed in Fig. 1(b). On the other hand, the emission from the *n*-GaAs doped layer is only slightly negative polarized [see Fig. 1(b)]. The resulting total polarization from the contact layer emission is ~−60% for all bias voltages, and it is mainly dominated by the polarization of the substrate recombination, since this transition dominates over the other two for all bias. In contrast, the circular polarization from the QW is smaller than the contact layers but it presents a strong dependence on both the excitation intensity and the applied bias voltage. Here again, the effect of the excitation intensity on the QW polarization is only obliterated in the bias voltage range (0.25–0.40 V) where the density of photogenerated holes does not exceed the electron density even under high excitation conditions. For the other voltages, the increase of the hole density in the structure induces a shift of the QW circular polarization to positive values. In fact, the QW polarization actually becomes positive for bias >0.6 V under a high excitation intensity.

As we mentioned above, the circular polarization of the QW emission does not follow the measured spin-splitting energy from this emission [see Figs. 1(c) and 1(d)]. Therefore, it cannot be solely attributed to a simple thermal occupation effect of the QW excitonic states, which have rather small effective *g* factors. The dependence of the QW polarization on the bias voltage is, in fact, rather complex and probably involves other effects such as the alignment of the spin-split QW levels at the resonant condition, the spin polarization of the separated electrons and holes prior to their tunneling into the QW, and if they maintain their spin polarization during the tunneling process. In a simple qualitative analysis, we do observe a correlation between the spin polarization of the carriers prior to tunneling effect and our results. We have demonstrated that the electrons in the contact layer are strongly spin polarized resulting in a large negative circular polarization emission. On the other hand, based on the literature we expect that the *g* factor for holes favors a positive polarization.[18,19] This balance between GaAs electron/hole *g* factors, with similar modulus and opposite signs, actually explains the excitonic *g* factor being almost zero for this material. The tendency of the QW polarization to become more positive as we increase the laser intensity may thus be associated to an increased number of holes that maintain their polarization as they tunnel in the QW. This is also in qualitative agreement with previous results in a *p*-type RTD (Ref. 12) where the QW circular polarization was positive due to the majority holes in this structure, except for bias voltages where the photogenerated electrons resonantly tunnel into the QW, when the polarization became negative.

In conclusion, we have observed that the QW circular polarization in an asymmetric *n*-type RTD can be controlled by the bias voltage and light illumination. For instance, when the structure is biased with ~0.8 V and the light excitation is increased by a factor of 5, we observe a variation of the circular polarization from −40% to +5%. The same variation can be obtained with a constant illumination by varying the bias from 0.4 to 0.8 V. We associated this large variation of polarization to the accumulation of photogenerated holes in the QW, which is greatly enhanced in our structure due to its asymmetric barriers. This effect may be explored to design other devices for spintronic applications.

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