Electroluminescence And Spin-Polarized Hole Injection In InAs/GaAs Quantum Dot Heterostructures

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Abstract. We demonstrate the feasibility to obtain electroluminescence (EL), up to room temperature, from self-assembled quantum dots included in a Schottky diode. Moreover, using a ferromagnet as the contact layer, sizable circular polarization of the emission in the presence of an external magnetic field (*B*) is obtained. A resonant behavior of the degree of circular polarization as a function of applied voltage, for a given *B*, is observed. We explain our findings using a model including tunneling through the metal-semiconductor interface, transport in the near surface region of the heterostructure and out-of-equilibrium statistics of the injected carriers.

Keywords: spin injection, quantum dot, Schottky diode
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INTRODUCTION

Incorporation of self-assembled quantum dots (SAQDs) into a Schottky diode (SD) offers a number of potentially interesting applications. First, it makes possible to realize a light-emitting device with SAQDs covered with a very thin capping layer and emitting at a wavelength up to 1.6 μm [1]. Secondly, this is a promising way of spin injection into the dots, which is of great importance for spintronics [2]. During the last years, reverse-biased SDs have been used as a tool for studies of the spin injection from ferromagnetic metals (FMs) to semiconductor layers [3, 4]. In such structures, the injection occurs via tunneling through the barrier depending on the doping level of the semiconductor. We pursue a different approach.

In an earlier work [5] we have shown the viability to achieve a high degree of circular polarization (up to ≈ 40%) of the electroluminescence (EL) in a forward-biased FM-SD based on an InAs/GaAs quantum well (QW) heterostructure (HS) under applied magnetic fields. This effect was explained in terms of injection of spin-polarized minority carriers from the FM to the semiconductor HS via tunneling. Here we demonstrate the feasibility to obtain a similar EL effect for quantum dots.

EXPERIMENTAL DETAILS

InAs/GaAs SAQD heterostructures were grown on *n*-type GaAs substrates by atmospheric-pressure metal-organic vapor-phase epitaxy. The QDs were overgrown by an InGaAs QW layer (2 nm) and covered by a GaAs capping layer, with variable thickness (10 to 30 nm). Two kinds of layers were used for the Schottky contacts: Au (normal) and Au-Ni-Au (FM). The samples were placed in a helium-bath cryostat at 2.5 K and circularly polarized EL, with direct bias ranging from 1 to 2 V, was measured in Faraday geometry, for magnetic fields up to 10 T. For regular EL experiments, the samples were mounted on the cold finger of a variable-temperature cryostat. The signal was dispersed with a spectrometer and detected with a liquid-nitrogen cooled InGaAs photodiode array. A quarter-wave plate in combination with a linear polarizer was used to select the EL with left and right circular polarizations.

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RESULTS AND DISCUSSION

Our HSs show good luminescence properties, with the emission bands located at 1.2-1.3 eV for the QW and at 0.8-0.95 eV for the QDs (see Fig. 1). The current-voltage characteristics of similar diodes were described before [6] and allowed for the determination of the Schottky barrier height (0.7-0.9 eV). The EL spectra show several peaks corresponding to the electron-hole transitions involving the ground and excited states in QDs. The EL intensity depends strongly on the pumping current (i.e. applied bias) and temperature: it exhibits an exponential growth with increasing bias, at low voltages, followed by a power law above a threshold (V_t, of the order of the band-gap energy of GaAs); it raises markedly with increasing temperature below V_t, while a much weaker temperature dependence is obtained for higher voltages. The capping layer thickness plays also an important role on the EL characteristics.

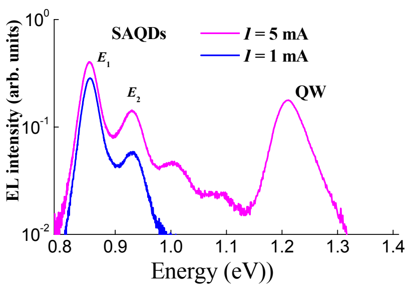

FIGURE 1. EL spectra of a SD with Au contact measured for two different values of pumping current. The spectra show several emission peaks originating from the ground (E_1) and excited (E_2) states of the SAQDs and the QW. T=77 K.

These experimental findings are well reproduced by our modeling that includes the following steps:
(i) Calculation of the electron and hole tunneling currents in the SD structure with oxide layer;
(ii) Determination of the minority carrier's generation rate in the SAQDs and QW by a simplified analysis of the diffusion-drift transport in the near-surface region;
(iii) Calculation of minority carrier's statistics out of equilibrium and determination of the light emission rates [7].
The modeling results (to be published elsewhere) convinced us that the EL of our direct-biased SDs indeed is due to the tunneling-mediated injection of holes from the metal into the light-emitting zone (SAQDs and QW).

In the presence of magnetic field, the degree of circular polarization, P, is determined by the nature of the contact metal. Samples with Au contacts display a left-handed polarization, while for the diodes with ferromagnetic contacts, a right-handed polarization is obtained (see Fig. 2). The former fact can be attributed to the Zeeman splitting of the hole levels in the QDs, while the latter is due to the injection of spin-polarized holes from the FM Schottky contact, as confirmed by the larger values of P for the second emission peak (P =+8% at 10 T). The lower values of P obtained for QDs, as compared with those in similar experiments in QWs [5], may be attributed to a different ordering of the Zeeman-split levels in both systems. The degree of circular polarization for the samples with ferromagnetic contacts shows a non-trivial behavior that depends mainly on the capping layer thickness and voltage. At 10 T, P reaches a maximum at a voltage slightly above V_t. The tuning by the voltage of the Fermi level of the spin-split hole sub-bands in the metal with respect to the top of the valence band in the capping layer is responsible for this non-monotonic behavior.

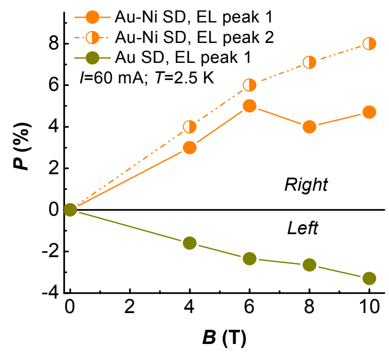

FIGURE 2. Degree of circular polarization *vs* magnetic field for two SDs with FM and Au contacts made on the same HS. For the FM SD, data for the EL peaks E_1 and E_2 are presented.

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