# Surface-emitting spin-polarized $In_{0.4}Ga_{0.6}As/GaAs$ quantum-dot light-emitting diode

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(Received 12 October 2001; accepted for publication 14 November 2001)

We report the properties of a spin-polarized $In_{0.4}Ga_{0.6}As/GaAs$ quantum-dot surface-light-emitting diode with a $Ga_{0.974}Mn_{0.026}As$ spin injector layer. Spin-polarized holes from this ferromagnetic layer recombine with electrons in the quantum dots to produce circularly polarized light output. The peak optical polarization efficiency at 5.1 K is 18% and the spin injection efficiency is estimated to be ~36%. The temperature dependence of spin injection is almost identical to the temperature dependence of magnetization in the (Ga, Mn)As layer. 
[DOI: 10.1063/1.1436526]

The control of spin, in addition to the charge of the carriers in semiconductor devices, can provide information storage and processing capabilities at the same time.[1,2] Polarized light emitters, detectors, and optical interconnects can be used for applications such as optical switching, optical communication with increased bandwidth, and others yet to emerge. An elegant technique to realize a polarized light emitter, utilizing the injection and recombination of spin-polarized carriers, has been demonstrated with both III–V (Ref. 3) and II–VI (Refs. 4 and 5) -based heterostructures. Spin-polarized electrons or holes are injected from a spin-injection (or spin-aligner) layer across a suitably spacer layer and made to recombine with unpolarized carriers of the opposite type in the active region. The degree of the optical polarization of the light output is ideally half of the spin polarization of the current.[4,5] In general, the spin injection of electrons is better than that of holes due to reduced spin-orbit coupling in the conduction band, leading to a decreased spin decoherence.[4] The spin-injector layer is usually a dilute magnetic semiconductor (DMS). Collective polarization in a DMS provides a large magnetic moment. The dilute III–V alloys (Ga, Mn)As, which are ferromagnetic semiconductors, provide a localized magnetic moment and holes. An exchange interaction between localized spins of the Mn atoms and the holes leads to a large *g* factor and a large Zeeman splitting.[6,7] With a suitable spin scatterer, all the holes scatter to the lower Zeeman levels, leading to a high percentage of spin-polarized holes. The easy axis of the magnetization in (Ga, Mn)As is in the plane of the layer.[1] Spin injection in such ferromagnetic semiconductors does not require an external magnetic field. The seamless integration of ferromagnetic semiconductors with nonmagnetic regions allows efficient injection of spin-polarized carriers and avoids the problems encountered in spin injection across ferromagnetic metal–semiconductor contacts.[8,9]

In the experiments reported to date,[3,4] quantum wells have been used as the active, or recombination, region in which spin-polarized carriers recombine to produce circularly polarized photons. Quantum dots can be a more suitable

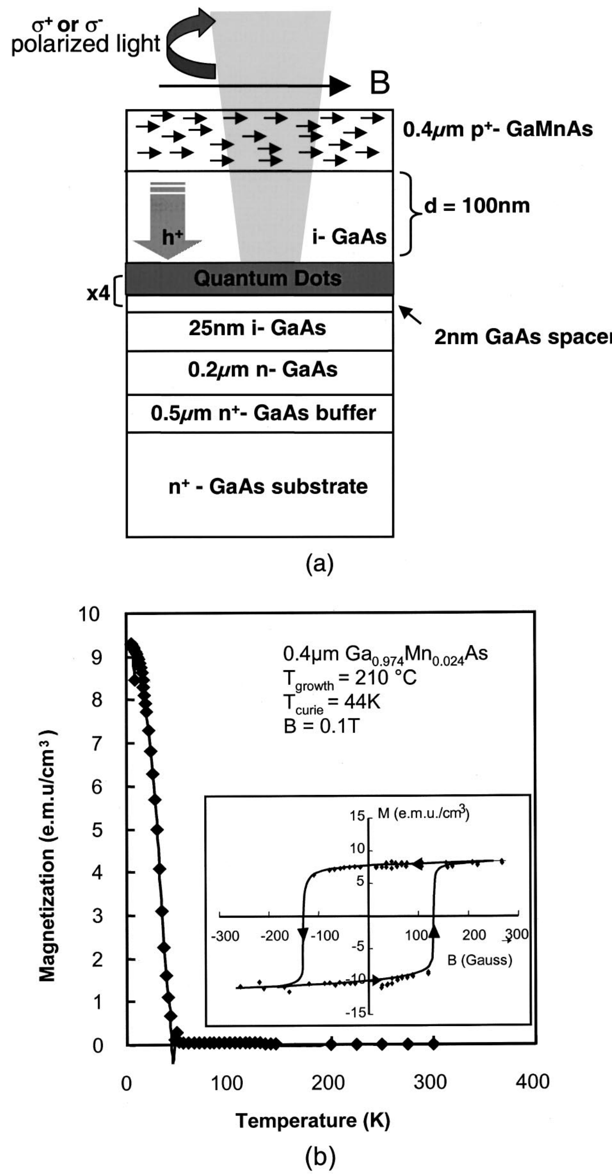


FIG. 1. Heterostructure schematic of the surface-emitting spin-polarized quantum-dot surface-light-emitting diode grown by solid-source molecular-beam epitaxy with a Mn source. (b) Magnetization vs temperature data for the (Ga, Mn) As spin-aligner layer. Inset shows the characteristic hysteresis behavior for the (Ga, Mn) As layer recorded at $T=8$ K.

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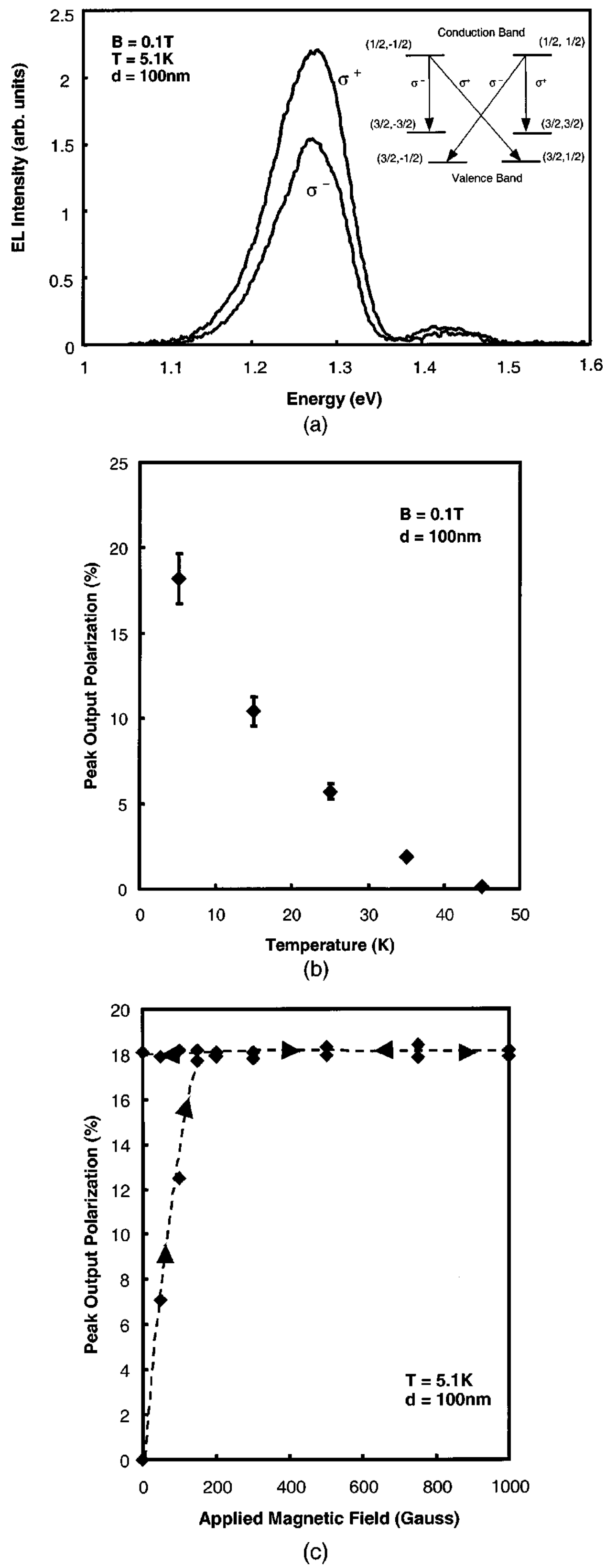


FIG. 2. (a) Measured electroluminescence spectra for the right circular ($\sigma^+$) and left circular ($\sigma^-$) polarized light measured at 5.1 K with an applied magnetic field of 0.1 T. Inset shows the spin-degenerate conduction-and valence-band states and the corresponding radiative transitions. (b) Measured temperature dependence of the peak output polarization. (c) Hysteresis behavior in the output polarization and the remanent polarization at $B=0$.

recombination media for the following reasons: (a) the spin-relaxation time in quantum dots, as determined from recent pump–probe experiments, is longer than that in quantum wells;[10,11] and (b) the interband ground-state transition energy of the InGaAs/GaAs quantum dots is considerably smaller than the band gap of GaMnAs. We have, therefore, investigated the growth, fabrication, and characteristics of a polarized III–V quantum-dot light emitter. Spin-polarized holes from a GaMnAs spin aligner recombine with electrons in a self-organized $In_{0.4}Ga_{0.6}As$/GaAs quantum-dot active region separated from the ferromagnetic layer by a GaAs spacer. Circularly polarized surface emission is observed from the mesa-shaped light-emitting diodes.

The quantum-dot light-emitting diode (LED) heterostructure, shown in Fig. 1(a) was grown by molecular-beam epitaxy on a Si-doped $n^+$ (001) GaAs substrate. Doped and undoped GaAs layers were grown at a substrate temperature of 600 °C. The undoped active region, consisting of four coupled $In_{0.4}Ga_{0.6}As$ self-organized quantum-dot (QD) layers, were grown at 520 °C. After growth of the undoped GaAs spacer layer, varying in thickness from 350 to 1000 Å, the 0.4 $\mu$m (Ga, Mn)As spin-injector layer was grown at 210 °C. A Mn composition of 2.6% in the layer is confirmed from x-ray diffraction measurements. The magnetization in the ferromagnetic alloy was measured as a function of temperature using a superconducting quantum interference device magnetometer. The temperature-dependent magnetization is shown in Fig. 1(b), indicating a Curie temperature, $T_c$, ~44 K. The magnetization also exhibits the characteristic hysteresis behavior, as shown in the inset of Fig. 1(b), with a saturation field of ~150 Oe. It was also confirmed that the easy axis of magnetization is in the plane of the sample. Similar measurements were made on a nonmagnetic control sample with a Be-doped GaAs contact layer on top. No magnetization was observed in these samples at any temperature. Therefore, the magnetization and hysteresis therein observed in the samples with ferromagnetic layers are attributed to the latter. Mesa-shaped diodes, 200 $\mu$m in diameter and with a top ring contact, were fabricated by standard photolithography, wet-chemical etching, and metallization techniques. Identical diodes were also fabricated with the heterostructure in which the GaMnAs layer is replaced by a Be-doped GaAs layer. All the diodes showed excellent rectifying characteristics with a reverse breakdown voltage of 13 V.

Electroluminescence (EL) measurements were made with the LEDs at temperatures below the measured Curie temperature by mounting the devices in a Oxford Instruments liquid-He cryostat with a superconducting magnet. The LEDs were forward biased with a dc current source. The unpolarized electroluminescence at 5.1 K is characterized with a peak at 1.27 eV and linewidth (full width at half maximum) of 67 meV. All the measurements for the observation of the polarized light output were made with an applied magnetic field of 1000 Oe. The light output of the LED was focused onto a zero-order quarter-wave plate, which converts the circularly polarized output light into horizontal and vertical linearly polarized light. The latter is analyzed with a Glan–Thompson linear polarizer. The analyzed light is then focused onto a scanning spectrometer and the output is detected with a liquid-$N_2$-cooled photomultiplier tube. The background polarization of the measurement system was recorded prior to switching on the magnetic field. This is principally the polarization of the spectrometer. Results are reported here for a LED with a 1000 Å GaAs spacer between the QD region and the (Ga, Mn)As layer. The EL spectra, at 5.1 K, of the circularly polarized light ($\sigma^+$ and $\sigma^-$) output are shown in Fig. 2(a). The conduction- and valence-band states in the quantum dots and the expected radiative transitions are shown in the inset. The heavy-hole (hh) and light-hole (lh) transitions are polarized in opposite directions and the transition probabilities of the hh transitions are three times larger than those of the lh transitions. The optical polarization of the output is given by $P_{opt}=(\sigma^+-\sigma^-)/(\sigma^+ +\sigma^-)$. Here, $\sigma^+$ and $\sigma^-$ correspond to the polarization of the hh and lh transitions, respectively. The peak output optical polarization, $P_{opt}$, is shown in Fig. 2(b) as a function of measurement temperature. The temperature dependence of the output polarization agrees well with the temperature dependence of the magnetization. The peak output optical polarization at 5.1 K is ~18%, which translates to a spin-injection efficiency of ~36%. The remanent optical polarization of ~18% at 5.1 K for $B=0$ is shown in Fig. 2(c). No optical polarization was observed in the output of the control LEDs with a Be-doped GaAs contact layer.

The spin-injection efficiency and the optical polarization in the output of the quantum-dot LEDs are higher than similar quantum-well devices, as expected. We believe this is due to the longer carrier spin-relaxation times compared to those in quantum-well devices. However, in spite of this advantage, the polarization of the emitted light is low. This is because the hole spin in bulk GaAs is quite unstable. Second, because of the highly asymmetric shape of the self-organized quantum dots (the base is 3–4 times larger than the height) and due to the strong biaxial component of the strain in them, the optical selection rules may be very different from those in ideal quantum dots and more akin to quantum wells.[12] As mentioned earlier, one of the advantages arising from the recombination of spin-polarized carriers in the $In_{0.4}Ga_{0.6}As$ quantum dots is that the energy of the resulting circularly polarized luminescence (1.27 eV) is considerably smaller than the band gap of the $Ga_{0.974}Mn_{0.026}As$ spin aligner. Therefore, in spite of the Zeeman splitting in this layer, field-induced dichroism should be negligible. Finally, it may be noted that the device demonstrated here is also a detector of spin-polarized carriers.

In conclusion, we report the characteristics of surface-emitting spin-polarized light-emitting diodes in which the polarized light output results from the recombination of spin-polarized holes in quantum dots. A (Ga, Mn)As layer is used as the spin injector and *p*-type contact layer of the diode. We estimate spin-injection efficiencies up to 36% at 5.1 K, as inferred from the measured optical polarization of the electroluminescence.

The authors acknowledge useful discussions with Professor J. Singh and Professor D. Steel. The work is being supported by the Army Research Office (MURI program) under Grant No. DAAD 19-99-1-0198.

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