Optical Detection of Hot-Electron Spin Injection into GaAs from a Magnetic Tunnel Transistor Source

X. Jiang,[1,2] R. Wang,[1,2] S. van Dijken,[1] R. Shelby,[1] R. Macfarlane,[1] G. S. Solomon,[2] J. Harris,[2] and S. S. P. Parkin[1]
[1]*IBM Research Division, Almaden Research Center, San Jose, California 95120, USA*
[2]*Solid State and Photonics Laboratory, Stanford University, Stanford, California 94305, USA*
(Received 31 December 2002; published 23 June 2003)

Injection of spin-polarized hot-electron current from a magnetic tunnel transistor into GaAs is demonstrated by the observation of polarized light emission from a $GaAs/In_{0.2}Ga_{0.8}As$ multiple quantum well light-emitting diode. Electroluminescence from the quantum wells shows a polarization of ~10% after subtraction of a linear background polarization. The polarization shows a strong dependence on the bias voltage across the diode, which may originate from changes in the electron spin relaxation rate in the quantum wells under varying bias conditions.

DOI: 10.1103/PhysRevLett.90.256603 PACS numbers: 72.25.Hg, 72.25.Ba, 72.25.Dc, 72.25.Rb

The dream of spin-based electronics has inspired much research into the transport and manipulation of electron spins in semiconductors and metals [1]. The long spin lifetimes and the possibility to transport spins coherently over large distances in semiconductors [2,3] promise a new generation of microelectronic devices based on the spin degree of freedom [4–7]. Their development, however, is currently limited by the absence of a suitable source of highly spin-polarized electrons operating above room temperature. While the injection of the spin-polarized current into semiconductors from dilute magnetic semiconductors has been demonstrated [8–10], these materials exhibit magnetic ordering temperatures well below room temperature, thereby limiting their usefulness. By contrast, ferromagnetic (FM) metals display high magnetic ordering temperatures but, so far, direct electrical spin injection from such metals into semiconductors using diffusive contacts shows low efficiency [11–13] and, in any case, may be fundamentally limited by the substantial conductivity mismatch between metals and semiconductors [14].

Recently, spin injection from ferromagnetic metals across tunnel barrier contacts into semiconductors has made promising progress [15–19], but in this approach the polarization of the injected electrons is limited by the spin-dependent tunneling of electrons at the Fermi energy of the metal. There is no such limitation in a magnetic tunnel transistor [20–22] in which the spin polarization of the injected electrons is determined by spin filtering in the base region of the device and can reach nearly 100% [23,24]. Moreover, the magnetic tunnel transistor is a three-terminal device, which allows the energy of these electrons to be varied over a wide range. In addition, since the electrons are injected ballistically into the semiconductor the device overcomes the fundamental conductivity mismatch problem [25].

In this Letter we demonstrate, for the first time, that the magnetic tunnel transistor is a useful source of spin-polarized hot-electron current for spin-based electronic devices. The spin polarization of electrons injected in GaAs is detected using a quantum well (QW) light-emitting diode (LED) structure.

The magnetic tunnel transistor is a three-terminal device combining a magnetic tunnel junction with a semiconductor collector as shown schematically in Fig. 1. A FM metal emitter injects spin-polarized hot electrons across a tunnel barrier into a FM metal base. These hot electrons traverse the base layer and are subsequently collected by the collector. Spin-dependent scattering in the base layer causes the electrons to lose energy and/or change momentum. Only electrons that maintain enough energy to surmount the Schottky barrier at the base/collector interface and that can find available states in the conduction band of the semiconductor collector are collected. As a result, the transmission of hot electrons into the collector is very sensitive to scattering processes in the base layer. Because of a large asymmetry in the

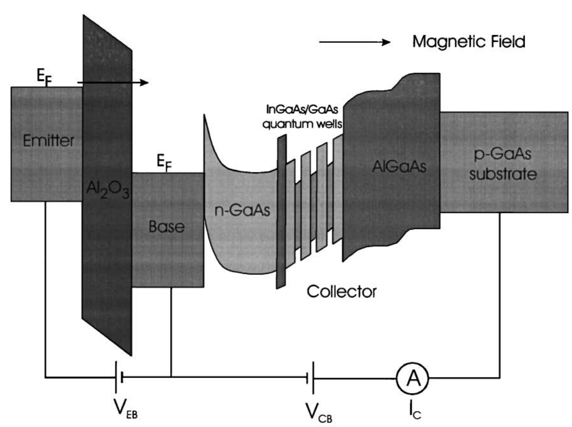

FIG. 1. Schematic energy band diagram of a magnetic tunnel transistor merged with a quantum well light-emitting diode collector. The emitter/base bias V_{EB} controls the energy of the injected hot electrons. The collector/base bias V_{CB} can be used to adjust the band bending of the LED.

majority and minority electron attenuation lengths in the base layer, majority electrons are preferentially collected. The hot-electron current can be nearly 100% spin polarized at the base/collector interface [24]. However, the degree of spin polarization that can be maintained after the electrons cross the metal/semiconductor interface remains an important question. In order to measure the spin-injection efficiency, a QW LED is incorporated as the collector of the magnetic tunnel transistor. The injected electrons recombine with holes in the QWs and emit photons. The polarization of emitted light is correlated to the spin polarization of the electrons according to the optical selection rules [26,27].

The semiconductor LED structure is grown by molecular beam epitaxy (MBE). Three p-$Al_{0.32}Ga_{0.68}As$ layers (total thickness 780 nm) with stepped doping concentration are grown on a Be doped p-GaAs substrate, followed by a 60 nm thick undoped $Al_{0.32}Ga_{0.68}As$ layer. Three $GaAs/In_{0.2}Ga_{0.8}As$ QWs are grown on top of the $Al_{0.32}Ga_{0.68}As$ layers with a well width of 8 nm and a barrier layer width of 15 nm. Another thin undoped $Al_{0.32}Ga_{0.68}As$ layer (5 nm) is then grown on top of the QWs. Finally, 100 nm n-GaAs (with a doping concentration of $\sim 5 \times 10^{16}$ cm^{-3}) is grown as the top layer to form a Schottky barrier with the FM base. The doping concentration of this top layer is optimized for the desired Schottky barrier characteristics. The $Al_{0.32}Ga_{0.68}As$ layers on both sides of the QWs help to confine electrons and holes within the wells to promote recombination, i.e., the $Al_{0.32}Ga_{0.68}As$ layers on the bottom prevent hot electrons from traveling deep into the p layer, while the thin upper $Al_{0.32}Ga_{0.68}As$ layer prevents holes from traveling into the lightly doped n layer. The $Al_{0.32}Ga_{0.68}As$ layers on the substrate side also prevent the Be dopants from diffusing into the QW region. Finally, a low temperature arsenic cap layer is deposited on the top surface to prevent oxidation and to protect the top surface after the sample is removed from the MBE chamber. After the MBE growth, the sample is transferred in air to an ultrahigh-vacuum sputtering chamber, where it is first heated up to ~520 °C to remove the arsenic cap. The sample is then cooled to room temperature and a magnetic tunnel junction is deposited on the semiconductor LED with dc magnetron sputtering. A sequence of three shadow masks is used to form the base layer, the emitter isolation pads, and the emitter layer, respectively [22]. The base layer consists of 3.5 nm $Ni_{81}Fe_{19}$ and 1.5 nm $Co_{84}Fe_{16}$ with the $Ni_{81}Fe_{19}$ layer adjacent to the semiconductor substrate. The Al_2O_3 tunnel barrier is formed by reactive sputtering of Al in the presence of oxygen. The thickness of the barrier is ~2.2 nm. The emitter consists of 5 nm $Co_{84}Fe_{16}$. A 5 nm thick Ta layer is used as the cap layer to prevent oxidation of $Co_{84}Fe_{16}$.

The device is placed in a superconducting magnet cryostat with optical access for spin-polarized luminescence measurements. A magnetic field perpendicular to the FM layers is applied to rotate their magnetic moments out of the film plane. The luminescence experiments are conducted in the Faraday geometry with the propagation direction of the light parallel to the magnetic field. The emitter/base bias voltage (V_{EB}) determines the energy of the injected electrons, while the collector/base bias voltage (V_{CB}) is used to adjust band bending of the LED (Fig. 1). A particular advantage of using InGaAs wells is that the QW luminescence energy is smaller than the GaAs band-gap energy so the substrate is transparent and the electroluminescence (EL) from the quantum wells can be collected through the substrate. This minimizes any possible magnetic circular dichroism arising from polarization-dependent transmission through the FM layers. A combination of a liquid crystal retarder and a linear polarizer is used to selectively analyze the circular polarization components of the emitted light as σ^+ (left hand) or σ^-(right hand). The spectrum of the selected component is measured with a grating spectrometer and a charge-coupled device.

The EL shown in Fig. 2 is measured with $V_{EB} = -2.06$ V and $V_{CB} = 1.0$ V at 1.4 K. The emitter and collector currents are 280 and 11.5 μA, respectively. The solid and open circles represent σ^+ and σ^- polarization components, respectively. Note that the width of the EL peaks is only ~2.5 nm which is limited by the

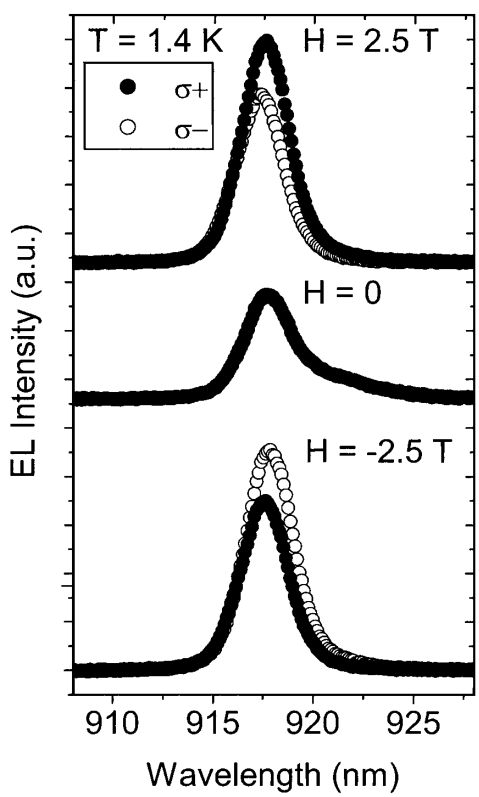

FIG. 2. Wavelength dependence of electroluminescence measured in magnetic fields of 2.5 T, 0, and −2.5 T at 1.4 K. The solid and open circles represent σ^+ and σ^- polarization components, respectively. The bias conditions are $V_{EB} = -2.06$ V, $V_{CB} = 1.0$ V.

spectrometer resolution for the given signal level. According to absorption studies, the separation in the wavelength between electron recombination with heavy holes and with light holes is ~40 nm in 8 nm wide $In_{0.2}Ga_{0.8}As$ QWs. Therefore, the narrow EL linewidth enables the unambiguous detection of electron-heavy hole recombination. In this case, the optical selection rules are very simple: the polarization of light is equal to the polarization of electron spins just before recombination [26,27]. The polarization of EL clearly depends on the magnetic field. At zero field, the intensities of σ^+ (I^+) and σ^- (I^-) components are the same. At high fields, there is a significant difference between I^+ and I^-. The polarization of EL, defined as $P_{EL} = (I^+ - I^-)/(I^+ + I^-)$ is ~13% at 2.5 T and ~ − 13% at −2.5 T. The sign of P_{EL} indicates injection of majority electron spins (− 1/2 spin state) into the QWs. This result is consistent with the sign of collector current polarization observed in electrical transport measurements in similar magnetic tunnel transistors [23]. Excitons in $In_{0.2}Ga_{0.8}As$ have a large g factor, leading to a large Zeeman splitting energy in the QWs, which is shown by the shift of the EL peak center positions for σ^+ and σ^- components at high fields. The overall intensity of EL at zero field is smaller than that at high fields. The origin of this field dependence is unclear at present. It may result from a change of recombination efficiency and/or spin relaxation rate in the QWs caused by the magnetic field.

In Fig. 3(a), P_{EL} is plotted as a function of magnetic field under the same bias conditions as described above. P_{EL} increases rapidly with the magnetic field up to ~2 T, where the magnetic moments of the FM emitter and base layers are expected to be completely rotated out of plane by the field. Above 2 T, P_{EL} still increases with the field. This is likely due to the background polarization caused by thermalization of the exciton spins in the magnetic field. The polarization P_C obtained after subtracting this linear background polarization from P_{EL} is shown in Fig. 3(b). A value of $P_C \sim 10\%$ is obtained at 2.5 T. Note that polarization-dependent reflection at the FM base/GaAs interface may give rise to a contribution to the EL polarization. However, we find that this effect is very small (< 1%) by passing linearly polarized light through the back side of the wafer and measuring the polarization of light reflected from the FM layers. The dashed line in Fig. 3(b) shows the magnetization of the FM layers measured with a SQUID magnetometer at 10 K for field oriented perpendicular to the sample. The field dependence of the sample magnetization is in excellent agreement with the field dependence of P_C confirming that P_C is related to the injection of spin-polarized hot electrons from the magnetic tunnel transistor injector.

Figure 4(a) summarizes the collector/base bias dependence of P_{EL} measured at a single field of 2.5 T. Below ~1 V the luminescence is too weak to measure P_{EL}. Above ~1 V, P_{EL} first decreases with increasing bias, then changes sign for $V_{CB} \sim 1.4$ V, and finally stays approximately constant at higher bias voltages. The sign reversal suggests that the injected electrons lose their initial spin orientation before recombination at high

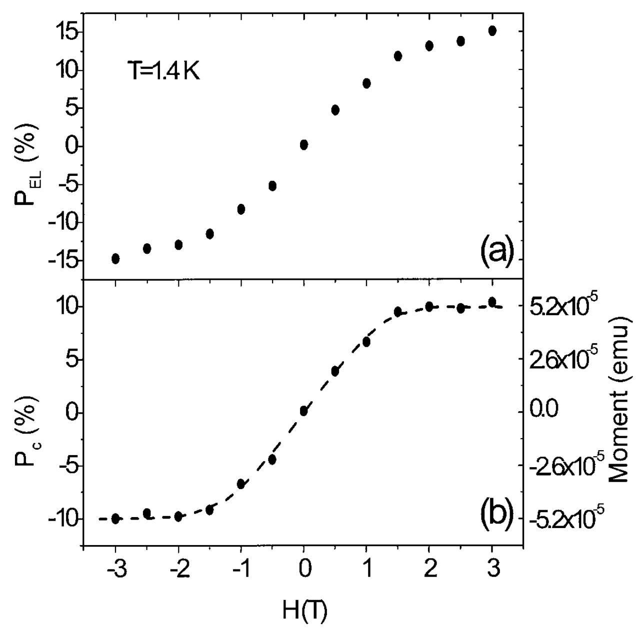

FIG. 3. The measured EL polarization P_{EL} (a) and the polarization after subtracting a linear background P_C (b) as a function of magnetic field at 1.4 K. The bias conditions are the same as those in Fig. 2. The dashed line in (b) shows the magnetic moments of the FM layers measured with a SQUID magnetometer at 10 K.

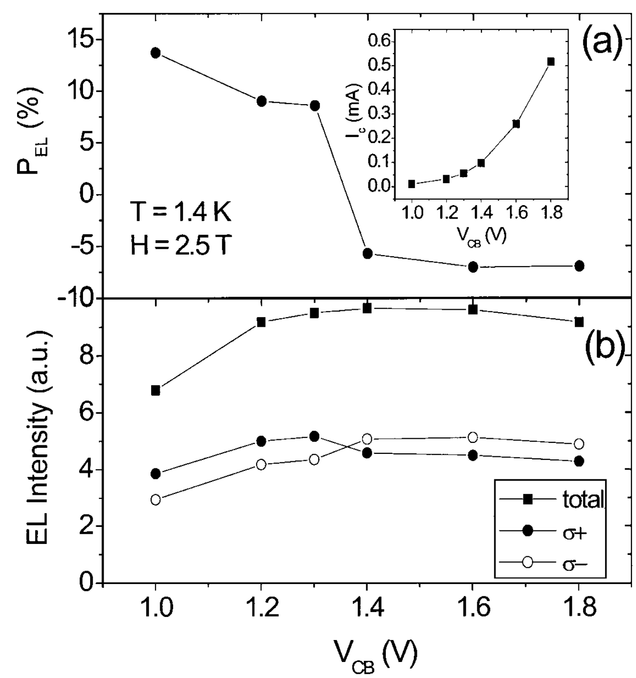

FIG. 4. The collector/base bias dependence of P_{EL} (a) and EL intensities (b) at 2.5 T. The inset in (a) shows the hole current as a function of V_{CB}. The emitter/base bias is $V_{EB} = -2.06$ V.

bias voltage due to a strong bias dependence of the spin relaxation rate in the semiconductor. Increasing V_{CB} results in an increasing hole current flowing from the p-GaAs substrate into the QWs [see the inset of Fig. 4(a)]. Electron-hole interactions can result in electron spins relaxing to the $+1/2$ state through the Bir-Aronov-Pikus mechanism [26]. When the hole concentration is low, the spin relaxation rate is proportional to the number of holes in the QWs. The spin relaxation rate is therefore expected to increase with increasing bias. However, above a certain critical hole concentration, the increase of the spin relaxation rate slows down because of the decrease of the Sommerfeld factor due to screening by the holes [26]. Consequently, the EL polarization does not decrease further with increasing bias. Other spin relaxation processes could also be influenced by the bias. For example, spin relaxation through the D'yakonov-Perel's (DP) mechanism is very sensitive to hot-electron energy [26]. At high bias, the conduction band of the n-GaAs region bends down more and the injected hot electrons would need to lose more energy to reach the bottom of the conduction band. During this process, they are more likely to lose their original spin orientation.

The bias dependence of the EL intensities at 2.5 T is summarized in Fig. 4(b). Increasing bias brings more holes into the QWs. As a result, electron-hole recombination becomes more efficient and the EL intensities go up with bias. However, when the bias is above $\sim$1.4 V, there are already enough holes in the QWs. Recombination is now limited by the number of electrons injected into the QWs and the total EL intensity stays approximately constant. Meanwhile, the intensity of the σ^+ component decreases significantly due to spin relaxation to the $+1/2$ state before recombination. This leads to the negative EL polarization at high biases.

The spin splitting in the GaAs conduction band is proportional to $E^{3/2}$, E being the electron energy. As a result, the DP mechanism becomes very effective at elevated electron energies [26]. The injected hot electrons lose a significant amount of polarization during the process of thermalization to the bottom of the conduction band. After the hot electrons enter the QW region, further spin relaxation can occur in the QWs before recombination [28]. The measured EL polarization indicates the electron spin polarization right before recombination with holes and, therefore, sets a lower bound on the spin-injection efficiency. It would be interesting to use other semiconductor collectors (e.g., Si or GaN), where the DP mechanism is not so important [26,29]. Under these circumstances the measured spin polarization should be larger.

In conclusion, the successful demonstration of the injection of spin-polarized hot-electron current into GaAs suggests that the magnetic tunnel transistor may be an important constituent of future spin-based electronic devices. While only modest values of spin-polarized current are inferred from these first experiments, these are limited by spin relaxation effects in the quantum well detector, so that higher values are likely in the future with improved understanding of this novel device.

This work is partially funded by a DARPA SPINS contract and a NEDO International research grant. The authors thank Zhigang Xie and Douglas King for their assistance with the sample growth and the optical setup.

[1] S. A. Wolf *et al.*, Science **294**, 1488 (2001).
[2] J. M. Kikkawa and D. D. Awschalom, Phys. Rev. Lett. **80**, 4313 (1998).
[3] J. M. Kikkawa and D. D. Awschalom, Nature (London) **397**, 139 (1999).
[4] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
[5] D. Loss and D. P. DiVencenzo, Phys. Rev. A **57**, 120 (1998).
[6] U. Žutic, J. Fabian, and S. D. Sarma, Phys. Rev. Lett. **88**, 066603 (2002).
[7] J. Fabian, I. Žutic, and S. D. Sarma, Phys. Rev. B **66**, 165301 (2002).
[8] R. Fiederling *et al.*, Nature (London) **402**, 787 (1999).
[9] Y. Ohno *et al.*, Nature (London) **402**, 790 (1999).
[10] B. T. Jonker *et al.*, Phys. Rev. B **62**, 8180 (2000).
[11] P. R. Hammar *et al.*, Phys. Rev. Lett. **83**, 203 (1999).
[12] S. Gardelis *et al.*, Phys. Rev. B **60**, 7764 (1999).
[13] C.-M. Hu *et al.*, Phys. Rev. B **63**, 125333 (2001).
[14] G. Schmidt *et al.*, Phys. Rev. B **62**, R4790 (2000).
[15] H. J. Zhu *et al.*, Phys. Rev. Lett. **87**, 016601 (2001).
[16] P. R. Hammar and M. Johnson, Appl. Phys. Lett. **79**, 2591 (2001).
[17] A. T. Hanbicki *et al.*, Appl. Phys. Lett. **80**, 1240 (2002).
[18] T. Manago and H. Akinaga, Appl. Phys. Lett. **81**, 694 (2002).
[19] A. F. Motsnyi *et al.*, Appl. Phys. Lett. **81**, 265 (2002).
[20] K. Mizushima *et al.*, IEEE Trans. Magn. **33**, 3500 (1997).
[21] R. Sato and K. Mizushima, Appl. Phys. Lett. **79**, 1157 (2001).
[22] S. van Dijken, X. Jiang, and S. S. P. Parkin, Appl. Phys. Lett. **80**, 3364 (2002).
[23] S. van Dijken, X. Jiang, and S. S. P. Parkin, Phys. Rev. B **66**, 094417 (2002).
[24] S. van Dijken, X. Jiang, and S. S. P. Parkin, Phys. Rev. Lett. **90**, 197203 (2003).
[25] E. I. Rashba, Phys. Rev. B **62**, R16 267 (2000).
[26] F. Meier and B. P. Zakharchenya, *Optical Orientation* (North-Holland, New York, 1984).
[27] C. Weisbuch and B. Vinter, *Quantum Semiconductor Structures: Fundamentals and Applications* (Academic, New York, 1991).
[28] T. Amand *et al.*, Phys. Rev. B **50**, 11 624 (1994).
[29] J. Fabian and S. Das Sarma, J. Vac. Sci. Technol. B **17**, 1708 (1999).