Room-Temperature Spin Injection from Fe into GaAs

H. J. Zhu, M. Ramsteiner, H. Kostial, M. Wassermeier, H.-P. Schönherr, and K. H. Ploog
Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, 10117 Berlin, Germany

(Received 12 April 2001; published 15 June 2001)

Injection of spin polarized electrons from a metal into a semiconductor is demonstrated for a GaAs/(In,Ga)As light emitting diode covered with Fe. The circular polarization degree of the observed electroluminescence reveals a spin injection efficiency of 2%. The underlying injection mechanism is explained in terms of a tunneling process.

DOI: 10.1103/PhysRevLett.87.016601 PACS numbers: 72.25.Hg, 72.25.Dc, 73.61.Ey, 75.50.Bb

Spin electronics has recently become a very intensely discussed topic in the solid state physics community [1–4]. A prerequisite for the realization of novel spin sensitive devices is the controlled injection of spin polarized carriers into a semiconductor [1]. Two recent approaches of spin injection are based on all-semiconducting devices. Fiederling *et al.* utilized the giant g factor of the paramagnetic II-VI semiconductor $\mathrm{Be}_x\mathrm{Mn}_y\mathrm{Zn}_{1-x-y}\mathrm{Se}$ to align the electron spin orientation obtaining an injection efficiency of 90% [5]. Ohno *et al.* used the ferromagnetic semiconductor $\mathrm{Ga}_x\mathrm{Mn}_{1-x}\mathrm{As}$ as a spin aligner and realized spin injection into GaAs with an efficiency of the order of 1% [6]. Regarding spin device applications, both approaches have the severe disadvantage to be restricted to low temperatures. The first approach, using a paramagnetic spin aligner, has the additional shortcoming that large external magnetic fields are needed during device operation. For these reasons, the ferromagnetic metal Fe is an excellent candidate for spin injection at room temperature. However, experimental evidence for spin injection from a metal into a semiconductor has not been achieved until now. Concerning Fe on GaAs, the formation of a magnetically dead layer at the Fe/GaAs interface has been discussed as an obstacle for spin injection [7]. Furthermore, there exists theoretical work predicting that spin injection from metals into a semiconductor should be almost impossible [8].

In this Letter, we demonstrate that spin injection from the ferromagnetic metal Fe into the semiconductor GaAs is indeed possible. The spin polarization of injected electrons is detected by the circular polarization of the electroluminescence in an $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$/GaAs light emitting diode (LED) [5,6].

The LED device structure (cf. Fig. 1, left inset) was grown by molecular beam epitaxy (MBE) on a p-GaAs(001) substrate with a 500-nm-thick p^+-GaAs buffer layer. The active region consists of two 4-nm-thick $\mathrm{In}_{0.2}\mathrm{Ga}_{0.8}\mathrm{As}$ quantum wells (QWs) separated by 10-nm-thick GaAs barriers and sandwiched between two 50-nm-thick undoped GaAs spacer layers. On top of this intrinsic region, a 70-nm-thick n^+-GaAs layer was grown. The subsequent growth of the 20-nm-thick Fe layer was carried out after transfer into the As-free metal MBE chamber connected to the III-V semiconductor MBE machine [9]. The growth rate for Fe was 0.2 nm/min and the growth temperature as low as 50 °C. Finally, the sample was capped with a 10-nm-thick Al protection layer. For reference purposes, the Fe was removed from part of the wafer and exchanged by a nonmagnetic AuGe alloy layer. After metal electrode deposition, the epitaxial wafer was processed into 50-μm-wide mesa stripes defined by dry chemical etching and cleaved into pieces of 240 to 670 μm length.

For the electroluminescence (EL) measurements, the LED was placed into a superconducting magnet system (OXFORD Spectromag 1000) with the temperature controlled in a continuous flow cryostat. The experiments were done in Faraday geometry, i.e., with the magnetic field direction parallel to the light propagation. The EL signal was collected from the wafer back side (cf. Fig. 1, left inset), dispersed in a triple spectrograph (DILOR XY800), and detected by a charge-coupled device (CCD) array. The circular polarization was analyzed by passing the EL light

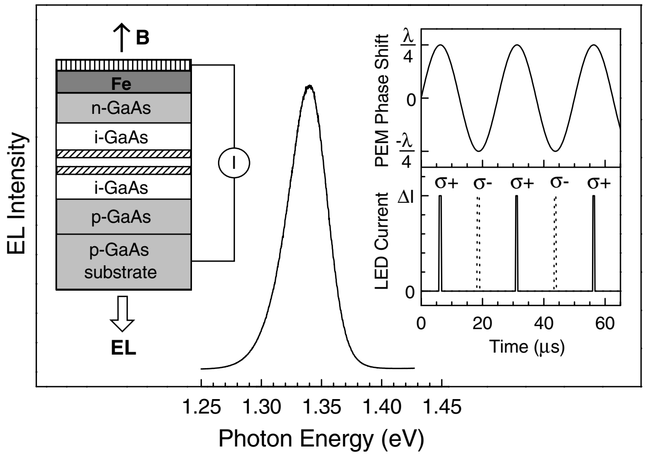

FIG. 1. Electroluminescence spectrum of LED with Fe cap layer recorded at 25 K. Left inset: Device structure showing the direction of the magnetic field (B) and the emitted light (EL). The (In, Ga)As QW layers are indicated by hatched areas. Right inset: Phase shift of PEM (upper) and LED current (lower) as a function of time. The LED current pulse sequence used to obtain I_+ (I_-) is indicated by the solid (dotted) line.

through a photoelastic modulator (PEM) [10] and a linear polarizer with its analyzing direction rotated by 45° with respect to the optical axis of the PEM. The LED was operated with short current pulses (0.4 μs pulse width at a frequency of 42 kHz) locked to the maximum or minimum phase shifts of the PEM. The degree of circular polarization is determined by $P = (I_+ - I_-)/(I_+ + I_-)$, where the right (left) circularly polarized component I_+ (I_-) is obtained for EL generation pulses locked to $+\lambda/4$ $(-\lambda/4)$ phase shifts of the PEM (cf. Fig. 1, right inset).

The EL spectrum of the LED at 25 K, shown in Fig. 1, reveals one peak at 1.338 eV in accordance with the design of the active region. The EL peak width of 33 meV is comparable to the expected heavy-hole/light-hole splitting [5]. Thus, the intensity component I_+ (I_-) of right (left) circularly polarized light has been determined by integrating over the low-energy part of the spectrum which can be safely attributed to heavy-hole transitions alone. In this case, the circular polarization degree $P = (I_+ - I_-)/(I_+ + I_-)$ is identical to the spin polarization of recombining electrons or heavy-holes [11]. The polarization degree P is shown in Fig. 2 (full squares) as a function of an external magnetic field B together with the out-of-plane magnetization curve (solid line) of the Fe layer independently obtained by spontaneous Hall effect measurements [12]. For magnetic fields $|B| < 4$ T, the polarization degree P follows very closely the magnetization curve of thin Fe layers. This coincidence strongly suggests that we observe injection of spin polarized electrons from Fe into GaAs with an efficiency of about 2%. The effect of spin injection is expected to be superimposed on the impact of electron and hole thermalization in GaAs due to the Zeeman splitting of spin-up and spin-down states. No saturation is expected for this kind of spin alignment, since the corresponding Zeeman splittings are smaller than the thermal energy kT for the whole range of external magnetic fields [13], which explains the observed deviation of the polarization degree P from the magnetization curve for magnetic fields $|B| > 4$ T.

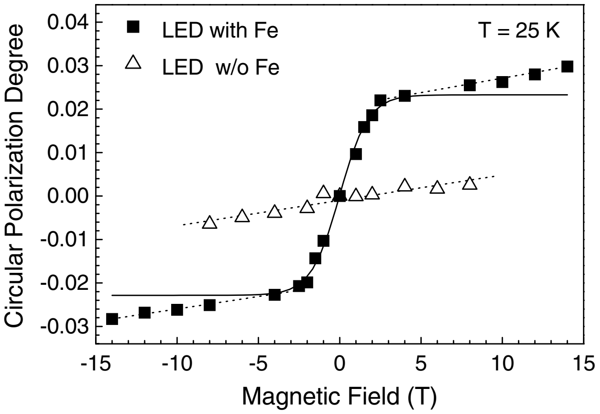

FIG. 2. Circular polarization degree P as a function of external magnetic field measured at 25 K from LEDs with (full squares) and without (open triangles) Fe cap layer. The out-of-plane magnetization curve of a thin Fe layer is shown for comparison in arbitrary units (solid line). The dotted lines are guides to the eye and indicate the contribution of the Zeeman splitting induced spin alignment in GaAs (see text).

The signatures of spin injection are not observed for the reference LED without Fe cap layer. This LED reveals a clearly smaller circular polarization degree P with a linear dependence on the magnetic field as shown in Fig. 2 (open triangles). This magnetic field dependence can be explained simply by the above-mentioned Zeeman splitting induced spin alignment in GaAs, without invoking any spin injection. The slope of the linear dependence is almost identical to that found for the LED with Fe cap layer in magnetic field range $|B| > 4\ T$, which strongly supports our conclusions.

It should be mentioned here that the geometrical configuration shown in Fig. 1 has been chosen to realize well-defined conditions for the demonstration of spin injection. In this geometry, the selection rules relating the circular polarization degree of the EL to that of the carriers are straightforward, but complicated for emission from a cleavage edge with the magnetic field direction perpendicular to the growth (quantization) direction. Furthermore, ambiguities due to passing the EL light through the magnetic Fe layer are avoided. The remaining possible artifact due to reflection of EL light at the GaAs/Fe interface is excluded by the results of the room-temperature measurements shown below. However, due to the shape anisotropy, the magnetic field direction corresponds to the hard out-of-plane axis of magnetization with a negligible coercitive field (no hysteresis behavior). For real spintronic device applications, in-plane magnetization would be chosen, where the magnetic hysteresis behavior can be utilized to sustain the spin injection properties without any external magnetic field.

When warming up the LED, the width of the EL peak increases up to 90 meV at room temperature (cf. Fig. 3), i.e., to a value, which is larger than the expected heavy-hole/light-hole splitting. This finding enables us to analyze both heavy-hole and light-hole transitions separately. The corresponding intensity components are determined by integrating over the low-energy and high-energy part of the EL peak for the heavy-hole and light-hole contribution, respectively (cf. shaded areas in Fig. 3). For a given polarization degree of injected electrons and unpolarized holes, we expect the same absolute value but opposite signs for the circular polarization degree P of both contributions (cf. schemes in Fig. 3) [5]. Indeed, Fig. 4 reveals the complementary behavior of P found for heavy-hole (full squares) and light-hole (open squares) transitions. Both circular polarization curves follow in the whole magnetic field range the Fe magnetization [12] shown in Fig. 4 (solid lines), where the magnetization curve is also shown with reversed sign for comparison with P of light-hole transitions. In fact, the impact of spin alignment due to the

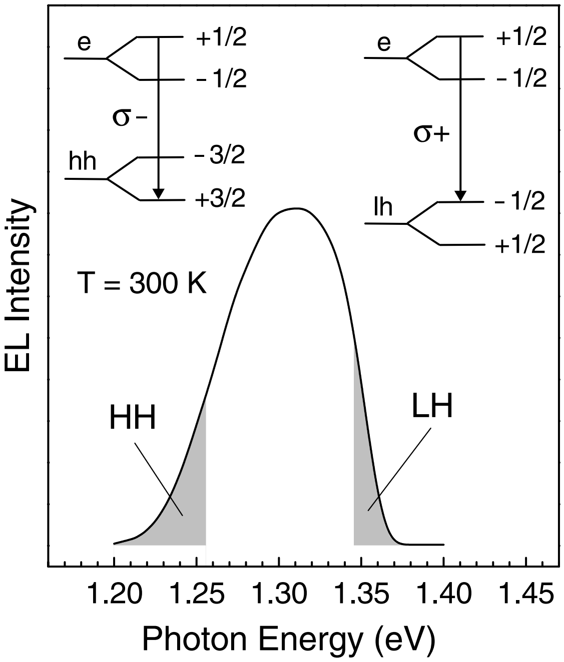

FIG. 3. Electroluminescence spectrum of LED with Fe cap layer recorded at 300 K. The shaded areas indicate the integrated intensities used to determine the circular polarization degree *P* for heavy-hole (HH) and light-hole (LH) transitions. The schemes indicate the circular polarization of the EL light from recombination of electrons with spin $+1/2$ for heavy-hole and light-hole transitions.

Zeeman splitting in GaAs is expected to be less pronounced at elevated temperatures. Our room-temperature results provide further evidence for the injection of spin polarized electrons from Fe into GaAs with an efficiency of 2%, which is enabled by the large Curie temperature of Fe. An artifact due to polarization dependent reflection of the EL light at the Fe interface is excluded, since the reflection properties of Fe do not produce the complementary behavior found for the heavy-hole and light-hole transitions. Furthermore, our results indicate that the very low growth temperature chosen for the Fe deposition [9] prevents the formation of a magnetically dead layer due to interdiffusion between Fe and GaAs, which destroys any spin information [7].

Our findings seem to be in contradiction to the theoretical work of Schmidt *et al.* [8] predicting the spin injection efficiency from a metal into a semiconductor to be limited to less than 0.1% due to the resistance mismatch. The reason for this apparent disagreement could be the fact that our Fe layers on GaAs form Schottky-type contacts which give rise to tunneling under appropriate bias conditions [14]. Thus, electrons from the Fe layer must tunnel through the Schottky barrier before reaching the active region of the LED. Such a tunneling process can lead to an enhanced spin injection efficiency, since it is not affected by the resistance mismatch [15]. Furthermore, the tunneling process is independent of the temperature in accordance with the constant injection efficiency of 2% observed between 25 and 300 K. Experimental evidence for spin polarized electron tunneling has been reported from measurements using a scanning tunneling microscope [16].

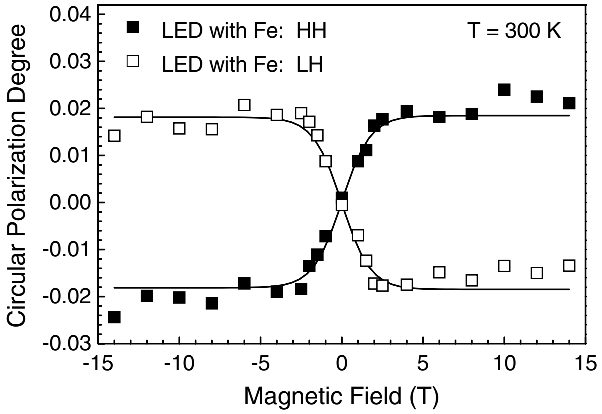

FIG. 4. Circular polarization degree *P* for heavy-hole (full squares) and light-hole (open squares) transitions as a function of external magnetic field measured at 300 K from LED with Fe cap layer. The magnetization curve of a thin Fe layer is shown for comparison in arbitrary units with two opposite signs (solid lines).

In conclusion, we have demonstrated room-temperature spin injection from a ferromagnetic metal into a semiconductor with an efficiency of 2%, which has previously been considered to be impossible. The injection mechanism is explained in terms of a tunneling process through a Schottky barrier. Further optimization of the Fe/GaAs interface as well as the device structure will lead to even larger efficiencies. This makes Fe a promising candidate for spin injection into semiconductors and paves the way for room-temperature operation of spintronics devices.

The authors thank K. J. Friedland for magnetization measurements as well as V. Sapega and H. T. Grahn for helpful discussions. Part of the work was supported by the Bundesministerium für Forschung und Technologie of the Federal Republic of Germany.

---

[1] M. Oestreich, Nature (London) **402**, 735 (1999).
[2] G. A. Prinz, Phys. Today **48**, No. 4, 58 (1995).
[3] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
[4] S. Gardelis, C. G. Smith, C. H. W. Barnes, E. H. Linfield, and D. A. Ritchie, Phys. Rev. B **60**, 7764 (1999).
[5] R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag, and L. W. Molenkamp, Nature (London) **402**, 787 (1999).
[6] Y. Ohno, D. K. Young, B. Beschoten, F. Matsukura, H. Ohno, and D. D. Awschalom, Nature (London) **402**, 790 (1999).
[7] Y. B. Xu, E. T. M. Kernohan, D. J. Freeland, A. Ercole, M. Tselepi, and J. A. C. Bland, Phys. Rev. B **58**, 890 (1998).
[8] G. Schmidt, D. Ferrand, L. W. Molenkamp, A. T. Filip, and B. J. van Wees, Phys. Rev. B **62**, R4790 (2000).

[9] H.-P. Schönherr, R. Nötzel, W. Q. Ma, and K. H. Ploog, J. Appl. Phys. **89**, 169 (2001).

[10] M. Wassermeier, H. Weman, M. S. Miller, P. M. Petroff, and J. L. Merz, J. Appl. Phys. **71**, 2397 (1992).

[11] B. T. Jonker, Y. D. Park, B. R. Bennett, H. D. Cheong, G. Kioseoglou, and A. Petrou, Phys. Rev. B **62**, 8180 (2000).

[12] K.-J. Friedland, R. Nötzel, H.-P. Schönherr, A. Riedel, H. Kostial, and K. H. Ploog, Physica (Amsterdam) **10E**, 442 (2001). The magnetization curves shown in Figs. 2 and 4 have been obtained experimentally for the present Fe layers on GaAs(001).

[13] Th. Wimbauer, K. Oettinger, Al. L. Efros, B. K. Meyer, and H. Brugger, Phys. Rev. B **50**, 8889 (1994).

[14] B. T. Jonker, E. M. Kneedler, P. Thibado, O. J. Glembocki, L. J. Whitman, and B. R. Bennett, J. Appl. Phys. **81**, 4362 (1997).

[15] E. I. Rashba, Phys. Rev. B **62**, R16 267 (2000).

[16] S. F. Alvarado and P. Renaud, Phys. Rev. Lett. **68**, 1387 (1992).