# Highly efficient room-temperature tunnel spin injector using CoFe/MgO(001)

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*Semiconductor spintronics is a promising technology in which the spin states of electrons are utilized as an additional degree of freedom for device operation. One of its prerequisites is the ability to inject spin-polarized electrons into semiconductors. An overview is presented of recent progress in spin injection using an injector based on a crystalline CoFe/MgO(001) tunnel structure. The spin polarization of the electrons that were injected into a GaAs quantum-well light-emitting diode was inferred from electroluminescence polarization from the quantum well. Spin polarizations of 57% at 100 K and 47% at room temperature were obtained. The spin polarization was found to exhibit a strong dependence on bias and temperature, which can be explained on the basis of spin relaxation within the GaAs.*

## Introduction

Conventional semiconductor electronics relies on manipulation of the charge states of electrons. In contrast, in the emerging field of spintronics, the spins of electrons play a central role.

Semiconductors have many intriguing properties that constitute a basis for the development of spintronic devices. For example, it has been found that the electron spin relaxation time in semiconductors can be several orders of magnitude longer than electron momentum and energy relaxation times [1]. Using an electric field, electrons in GaAs could be dragged over a distance of 100 $\mu$m without losing their spin coherence [2].

In addition to such long spin lifetimes and large spin diffusion lengths, semiconductors offer the flexibility of tailoring their band structures and carrier doping profiles to manipulate spins. For example, Ohno et al. showed that it is possible to control the ferromagnetism of InMnAs thin films by modulating the hole doping concentration [3]. Sandhu et al. and Karimov et al. demonstrated that electron spin relaxation rates in GaAs heterostructures can be varied by applying a gate voltage [4, 5]. Murakami et al. predicted that a dissipationless spin current flows in GaAs in the presence of an electric field [6]. These studies suggest that semiconductor spintronics has the potential for becoming the basis of a new generation of the microelectronic technology—with high-speed, high-density, low-power-consumption, and nonvolatile attributes [7, 8].

The functionality of semiconductor spintronic devices requires the creation, transport, manipulation, and detection of spin-polarized electrons. The first step, the creation of spin-polarized electrons, is often referred to as *spin injection*.

It has long been known that optical pumping with circularly polarized light can generate electrons with a certain spin orientation in direct-bandgap semiconductors [9]. For device applications, however, an electrical means for spin injection is much more desirable. The first attempts at spin injection into semiconductors were carried out using ohmic contacts formed by ferromagnetic metals [10–12]. Since the electrons in the ferromagnetic metals are spin-polarized, it was expected that the injected electrons would retain their spin orientation and thus give rise to successful spin injection. Despite significant efforts, however, unambiguous spin injection was not demonstrated. It was later realized that the conductivity mismatch between the metallic ohmic contact and the semiconductor might present a fundamental obstacle to the injection [13].

Efficient spin injection was first obtained using diluted magnetic semiconductors, such as BeMnZnSe, GaMnAs, and ZnMnSe as the spin injectors [14–16]. A very large spin-polarization—more than 80%—was



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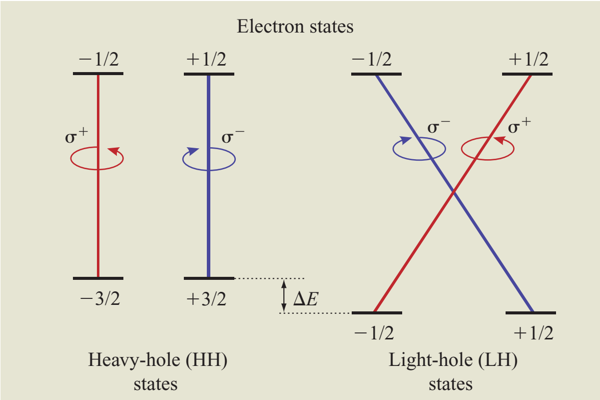



**Figure 1**

Optical selection rules for electron–hole recombination in the Faraday geometry. $\Delta E$ is the energy difference between the energy levels of the HH and LH states.

reported [17]. Such a large spin polarization is very useful for spintronics applications. However, the magnetic semiconductors, to date, display desirable magnetic properties only at temperatures well below room temperature and/or in the presence of large magnetic fields, thereby limiting their usefulness.

Ferromagnetic 3-*d* transition metals have Curie temperatures much higher than room temperature, making them attractive for spin injection into semiconductors. However, care must be taken to overcome the aforementioned conductivity mismatch between the metals and the semiconductors. Rashba first pointed out that this mismatch problem could be resolved if the ferromagnetic metal forms a tunnel contact with the semiconductor, since the tunneling process is spin-dependent and the tunnel contact can have high impedance [18]. This predication was experimentally confirmed by several groups using various types of tunnel contacts, including a thick AlGaSb barrier [19], Fe/GaAs Schottky tunnel contacts [20–23], and $Al_2O_3$ tunnel barriers [24–28]. Polarization values as large as ~30–40% were observed at low temperatures, while the polarization obtained at room temperature was much smaller.

When a Schottky or $Al_2O_3$ tunnel contact is used for spin injection, the maximum spin polarization that can be achieved might be limited by the tunneling spin polarization from the ferromagnetic metal. For instance, for 3-*d* transition metals and their alloys, the tunneling spin polarization is normally no more than 50% when an $Al_2O_3$ tunnel barrier is used [29]. One approach to overcome this limitation is to use a magnetic tunnel transistor as the spin injector [30], a three-terminal device in which use is made of efficient spin filtering of hot electrons in ferromagnetic metals to realize a highly spin-polarized electron source [31]. However, the output current of the magnetic tunnel transistor is relatively small. As a result, it must be operated at high electron energies in order to obtain a sufficient injection current. Unfortunately, electron spin relaxation becomes very rapid at these high energies, significantly reducing the observed electron spin polarization.

An alternative approach to increasing spin polarization is to use a crystalline MgO tunnel barrier. Using first-principles calculations, the tunneling spin polarization of a CoFe/MgO(001) structure was predicted to be very high [32–34]. It was found that in such a structure, for the majority electrons, the Bloch states with $\Delta_1$ symmetry decay slowly in the MgO barrier as evanescent states with the same symmetry. For the minority electrons, on the other hand, no Bloch states have $\Delta_1$ symmetry, leading to a rapid decay of these states in the MgO barrier. Experimentally, the tunneling spin polarization of CoFe/MgO junctions was measured using superconducting tunneling spectroscopy [35]. A large polarization (85%) was obtained, indicating that very efficient spin injection is possible using a CoFe/MgO tunnel injector.

In this paper, we present an overview of recent progress in spin injection experimentation using a CoFe/MgO tunnel injector [36, 37]. A GaAs quantum-well light-emitting diode (LED) was used to determine the spin polarization of the injected electrons. Polarization values as high as 47% were achieved at 290 K. The measured spin polarization showed strong bias and temperature dependences that were attributed to spin relaxation in the GaAs diode.

## Experimental studies

A quantum-well light-emitting diode is often used as an optical detector of the spin polarization of electrons injected into direct-bandgap semiconductors such as GaAs. The injected, polarized electrons travel to the quantum well, where they recombine with unpolarized holes from the substrate and emit light. By analyzing the circular polarization of the light, the spin polarization of the electrons can be determined. Use is made of optical selection rules [9] that apply in the Faraday geometry (with the spin orientation and light propagation direction both perpendicular to the plane of the quantum well), as depicted in **Figure 1**.

Two types of holes exist in the quantum well: heavy holes (HH) and light holes (LH); both can recombine with the electrons and emit photons with opposite helicity. In general, the electroluminescence (EL) spectra must be analyzed carefully in order to extract the spin polarization. However, in a quantum well, the energy degeneracy of the heavy- and light-hole states is lifted because of confinement and/or strain effects. If the energy splitting between the heavy- and light-hole energy levels is sufficiently large, it is possible to spectrally resolve the heavy-hole emission and measure only its circular polarization. In this case, the electroluminscence polarization is simply equal to the electron spin polarization prior to recombination. Because the selection rules depicted in Figure 1 are valid only in the Faraday geometry, a large perpendicular magnetic field is required experimentally to rotate the electron spins out of the film plane.

The quantum-well light-emitting diode detector is buried inside the semiconductor heterostructure. The injected electrons are first transported into the quantum-well region, where they spend a certain amount of time (characterized by the recombination time) before recombining with the holes and emitting light. The measured electroluminescence polarization does not include any spin-relaxation effects before recombination and therefore sets a lower bound on the spin polarization of the injected electrons. To properly interpret the experimental data, it is necessary to take into account various spin-relaxation processes in the semiconductor. Spin relaxation in semiconductors has been extensively studied, primarily through optical measurements [9, 38–42].

Three spin-relaxation mechanisms have been identified as being important here: the Elliott–Yafet (EY), D'yakonov–Perel (DP), and Bir–Aronov–Pikus (BAP) mechanisms. The EY process derives from the mixing of electron wave functions with opposite spin states due to spin-orbit coupling [43, 44]. Whenever an electron is scattered and changes its orbital momentum, the possibility of a spin flip exists. As a result, the EY spin-relaxation rate is proportional to the electron momentum-scattering rate. The DP process is present in semiconductors without inversion symmetry [45, 46]. The mobile electrons experience an effective magnetic field whose magnitude and orientation depend on the electron momentum. Spin precession around this magnetic field gives rise to spin relaxation. Momentum scattering randomizes the direction of the effective magnetic field and reduces the average precession effect. The DP spin-relaxation rate is therefore inversely proportional to the electron momentum-scattering rate, which is opposite to the EY process. The BAP process is due to electron–hole exchange and annihilation interactions [47]. An electron–hole pair recombines and emits a photon. This photon is subsequently reabsorbed and creates an electron–hole pair in different spin states. The relative importance of the three processes depends on sample structure and experimental conditions (semiconductor doping profile, experiment temperature, etc.).

The quantum-well LEDs used to determine the spin polarization of the injected electrons were fabricated using molecular beam epitaxy (MBE). First, three p-type AlGaAs buffer layers with stepped doping profiles were grown on a heavily doped p-type GaAs(001) substrate. The total thickness of the buffer layers was 5,700 Å. Subsequently, a 750-Å-thick undoped AlGaAs buffer layer was deposited. These buffer layers improved the growth quality of the quantum well and prevented dopant diffusion from the p-type substrate into the quantum well.

The active region of the LED, consisting of an undoped AlGaAs/GaAs quantum well, was grown above the buffer layers with a well width of 100 Å and a barrier thickness of 150 Å. The fabrication of the LED structure was completed with the deposition of a 1,000-Å-thick AlGaAs upper layer and a 50-Å-thick undoped GaAs capping layer.

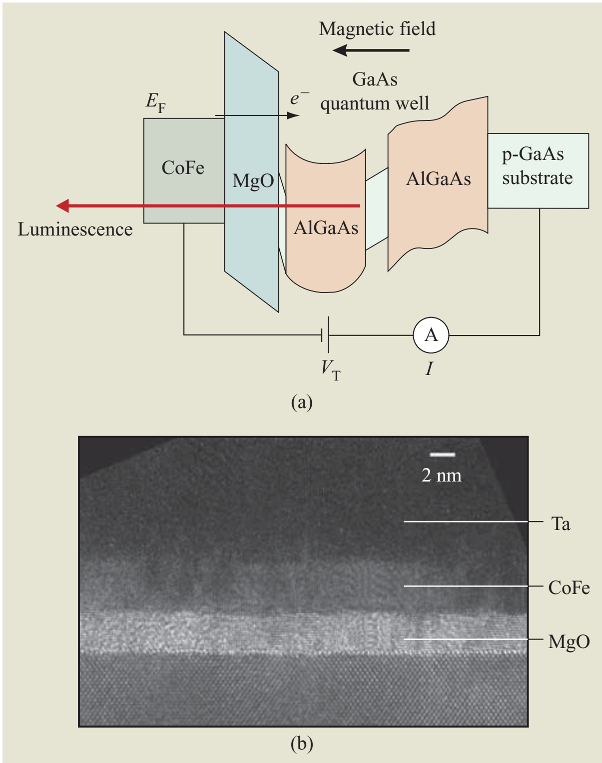
Two different LED samples were fabricated. For sample I, the AlGaAs composition was $Al_{0.08}Ga_{0.92}As$, and the upper AlGaAs layer was n-doped (Si, $5 \times 10^{16}$ $cm^{-3}$). For sample II, $Al_{0.16}Ga_{0.84}As$ was used, and the upper layer was p-doped (Be, $1 \times 10^{17}$ $cm^{-3}$). The LEDs were passivated with arsenic in the MBE chamber.

The LEDs were then transferred in air into a magnetron sputtering chamber in order to fabricate the spin injector. First, they were heated to 550°C to remove the arsenic cap. After they had cooled to ambient temperature, shadow masks were used to deposit an MgO tunnel barrier (~30-Å-thick MgO layer) and a ferromagnetic electrode (~50-Å-thick $Co_{70}Fe_{30}$ layer capped with an ~100-Å-thick Ta layer to prevent oxidation), thus forming the spin injector.

The MgO tunnel barrier was deposited by reactive sputtering in an argon and oxygen gas mixture. The CoFe and Ta layers were sputtered in pure argon gas. The active area of the spin injector was $\sim 100 \times 300$ $\mu m^2$. Finally, the samples were annealed at 300°C in vacuum for one hour.

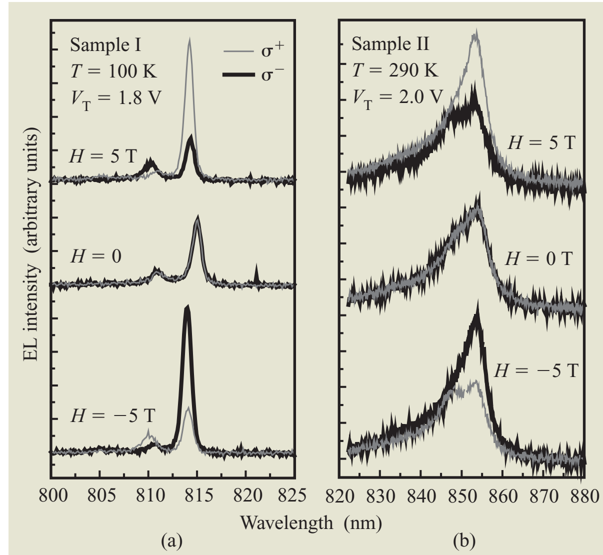
A schematic band diagram of the spin injection device is depicted in **Figure 2(a)**; **Figure 2(b)** shows a high-resolution transmission electron microscope (HRTEM) image of the CoFe/MgO spin injector. Both the MgO and CoFe layers were very smooth and were polycrystalline, with a strong (001) texture along the growth direction. Such crystallographic orientations are consistent with theoretically predicted orientations which should give rise to high tunneling spin polarization [32–34].

The electroluminescence polarization was measured in a cryostat equipped with a superconducting magnet. By applying a bias voltage ($V_T$) across the device, spin-polarized electrons were injected from CoFe into the quantum well, where they recombined with holes from the p-type GaAs substrate and emitted circularly polarized light. The light was collected from the front side of the sample, i.e., through the MgO and CoFe films. A combination of a liquid crystal retarder and a linear




## Figure 2

(a) Schematic energy band diagram and (b) HRTEM image of a CoFe/MgO tunnel spin injector.




## Figure 3

Electroluminescence (EL) spectra of (a) sample I at 100 K and (b) sample II at 290 K. The light and heavy curves in (a) and (b) represent the $\sigma^+$ and $\sigma^-$ circular polarization components of the luminescence, respectively. From [36], with permission; ©2005 American Physical Society.

polarizer was used to selectively analyze the circular polarization components of the emitted light as $\sigma^+$ (left-handed) or $\sigma^-$ (right-handed). The spectrum of the selected component was measured with a grating spectrometer and a charge-coupled device (CCD). The experiments were carried out at various temperatures and bias voltages in the Faraday geometry. Finally, the electron spin polarization was determined from the electroluminescence polarization using the selection rules.

The electroluminescence spectra for sample I at 100 K and sample II at 290 K are plotted respectively in **Figures 3(a)** and **3(b)**. The bias voltage was $V_T = 1.8$ V for sample I and 2.0 V for sample II. The electroluminescence peaks at longer wavelengths were due to recombination of electrons with the heavy holes in the quantum well, while the peaks at shorted wavelengths were due to recombination of electrons with the light holes and excited heavy holes. For both samples, the electroluminescence intensities of the left ($\sigma^+$) and right ($\sigma^-$) circular polarization components were found to be magnetic-field-dependent: The light intensities of the $\sigma^+$ ($I^+$) and $\sigma^-$ ($I^-$) components were coincident at zero field and became significantly different in high magnetic fields as the CoFe moment was rotated out of the film plane by the field. Here, $I^+$ and $I^-$ were calculated by integrating the areas under the peaks. The electroluminescence polarization (ELP) is defined as

$$ELP = \frac{I^+ - I^-}{I^+ + I^-}. \qquad (1)$$

As shown in Figure 3, the sign of the electroluminescence polarization indicates that majority electron spins were injected from CoFe into the quantum well.

Since the circular polarization of the heavy-hole emission has a simple relationship with the spin polarization of the electrons just prior to recombination, henceforth only the heavy-hole luminescence polarization is discussed, and it is referred to as $P_{EL}$. For sample I, the heavy-hole emission is well resolved in the spectrum because of its narrow linewidth (~10 Å). Therefore, it was straightforward to determine $P_{EL}$. In contrast, the heavy-hole peaks for sample II were broad at 290 K and were thus less well resolved. In order to extract $P_{EL}$ for this sample, the luminescence spectrum was fit with two Lorentzians and $P_{EL}$ was calculated from the fit.

The magnetic field dependences of $P_{EL}$ for sample I at 20 K and 100 K are depicted in **Figure 4(a)**. In each case the polarization increased rapidly with field up to ~2 T, when the CoFe moment was rotated completely out of plane. Above 2 T, $P_{EL}$ continued to vary with field approximately linearly, but at a much lower rate. Note that the slopes of the polarization above 2 T have opposite signs for the data at 20 K and 100 K. The linear variation of polarization with field above 2 T (hereafter referred to as the "background polarization") was observed over a wide temperature range. The slope of this background usually varied gradually from a negative value at low temperatures to a positive value at high temperatures, crossing zero at ~40–50 K. Several factors might contribute to the background polarization. At low temperatures, thermalization of electron spins in the quantum well due to Zeeman splitting could give rise to a negative background, since GaAs has a negative *g*-factor. At high temperatures, however, the Zeeman energy was negligible compared to $kT$, and therefore could not explain the observed background polarization. This background polarization was likely due to field-dependent spin relaxation and/or electron–hole recombination times. It is well known that a perpendicular magnetic field can suppress DP spin relaxation in GaAs [9], which would therefore give rise to a positive background. Moreover, it was found that the luminescence intensity from the quantum well increased with increasing fields, implying a shorter recombination time at higher fields that would also give rise to a positive background. Similar field dependences of $P_{EL}$ were observed for sample II, as plotted in **Figure 4(b)**. Very high electroluminescence polarization was obtained at 5 T for both samples: ~57% for sample I at 100 K and ~47% for sample II at 290 K.

The electroluminescence polarization after subtraction of the linear background (referred to as $P_C$) is shown in **Figures 4(c)** and **4(d)**. $P_C$ is a measure of spin polarization when the magnetic field influence on the polarization is excluded. Values as high as 52% and 32% were obtained at 100 K for sample I and at 290 K for sample II, respectively. The CoFe moment was measured at 20 K in a perpendicular magnetic field with a superconducting quantum interference device (SQUID) magnetometer. The results obtained are shown as solid lines in Figures 4(c) and 4(d). The SQUID data were scaled in order to facilitate comparison with the polarization data. The excellent agreement between the SQUID data and the polarization data confirmed that the large polarization originates from spin injection.

To rule out possible artifacts of our measurement setup, $P_{EL}$ was measured for a control sample, which had the same quantum well detector as sample I but had a nonmagnetic Pt layer in place of the CoFe layer. The light was collected through the MgO and Pt films. For this control sample, the polarization at 100 K was small (~1%) and showed a very weak field dependence. Since the electroluminescence signals of samples I and II were collected through the ferromagnetic CoFe layer,

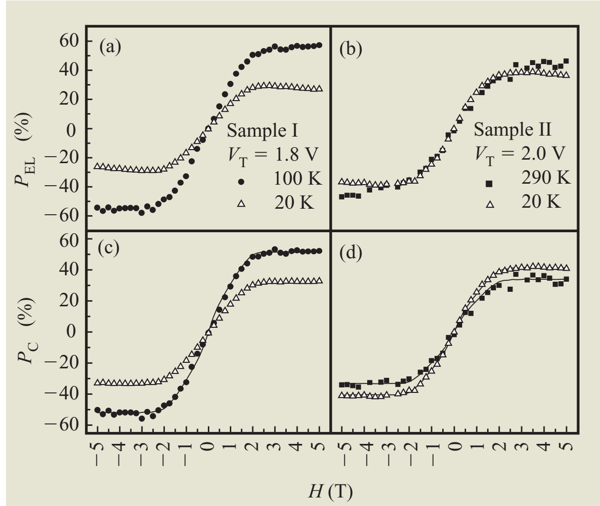
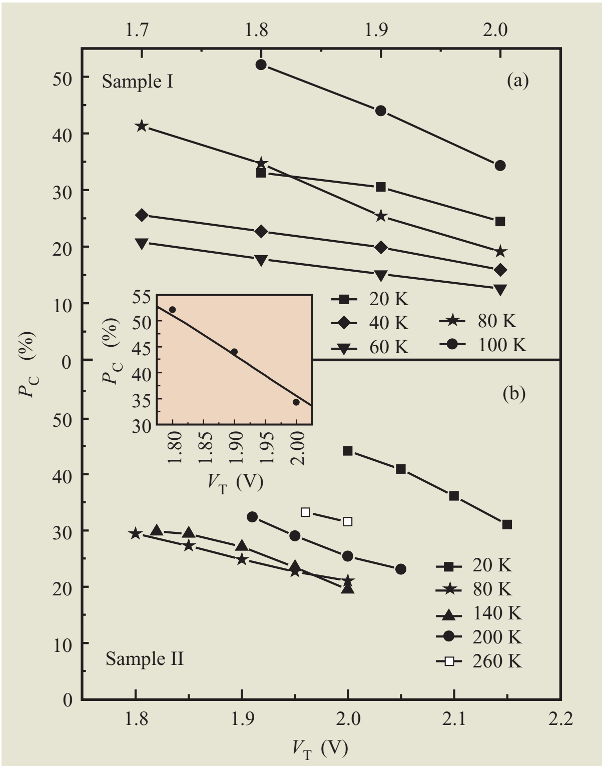



**Figure 4**

Magnetic field dependence of $P_{EL}$ [(a) and (b)] and $P_C$ [(c) and (d)] for sample I and sample II (represented by the symbols). The solid lines in (c) and (d) show the field dependence measured with a SQUID magnetometer. The latter have been scaled to permit comparison with the polarization data.

spin-dependent absorption and/or reflection might have contributed to the measured polarization. To check the magnitude of this effect, photoluminescence experiments with linearly polarized pump light were performed on samples I and II, giving a small polarization (<2%) and a weak field dependence. These results proved that the effects of polarization-dependent light absorption or reflection by the metal and semiconductor layers were very small.

The bias and temperature dependence of $P_C$ are shown in **Figure 5** for the two samples. The relatively small confinement potential of the $Al_{0.08}Ga_{0.92}As/GaAs$ quantum well resulted in weak luminescence signals at high temperatures, limiting the measurements of sample I to below 100 K. In contrast, measurements of sample II were possible up to room temperature owing to the use of a deeper $Al_{0.16}Ga_{0.84}As/GaAs$ quantum well. For both samples, $P_C$ decreased with increasing bias at a given temperature. A similar bias dependence was observed in optical experiments and was attributed to spin relaxation through the DP mechanism before photoexcited electrons reached the quantum well [48, 49]. In semiconductors lacking inversion symmetry, DP spin relaxation occurs because of spin precession about an effective magnetic field whose orientation and magnitude depend on the electron momentum. Larger electron momentum at higher bias results in a bigger effective field and consequently more rapid spin relaxation [9]. Note that




## Figure 5

Bias and temperature dependence of $P_C$ for (a) sample I and (b) sample II. The inset shows the calculated (curve) and measured (solid circles) bias dependence of $P_C$ for sample I at 100 K. Note the different bias voltage ranges for (a) and (b). Adapted from [36], with permission; ©2005 American Physical Society.

the luminescence intensity decreased at lower bias, therefore limiting the smallest bias voltages that could be used in our experiments.

A simple model can qualitatively account for the observed bias dependence. In this model, the measured polarization is calculated using the following formula:

$$P = P_I R_E R_{TH}, \tag{2}$$

where $P_I$ is the initial spin polarization of the injected hot electrons, $R_E$ is the amount of spin relaxation during the hot-electron thermalization process, and $R_{TH}$ is the amount of spin relaxation before the thermalized electrons recombine with holes. The conduction band spin splitting $\hbar\Omega$ in GaAs is equal to $AE_K^{3/2}$, where $E_K$ is the electron kinetic energy and $A$ is a proportionality factor. In our experiments, $E_K = V_T - E_g$, with $E_g$ being the bandgap energy of GaAs. In a rather simplified view, we assumed that the hot electrons lose their energy through a single scattering event with a time constant $\tau_E$; $R_E$ could then be expressed as

$$R_E = \frac{1}{\tau_E}\int_0^\infty \exp(-t/\tau_E)\cos(\Omega t)\,dt$$
$$= \frac{1}{1+(\Omega\tau_E)^2} = \frac{1}{1+A^2(V_T - E_g)^3\tau_E^2}. \tag{3}$$

The inset of Figure 5 shows a calculated bias dependence of $P_C$ (solid line) at 100 K for sample I together with the experimental data (solid circles). The parameters used in the calculations were $P_I R_{TH} = 62.5\%$, $A = 9.38\ \mathrm{ps}^{-1}\ \mathrm{eV}^{-3/2}$, $E_g = 1.4$ eV, and $\tau_E = 0.2$ ps. Despite the simplicity of the model, qualitative agreement between the calculation and the experiment could be obtained.

A non-monotonic temperature dependence of the electroluminescence polarization was found: $P_C$ decreased with temperature in the low-temperature regime, reaching a minimum at an intermediate temperature, then increased with temperature. This is clearly illustrated in **Figure 6**, where the bias voltages were $V_T = 1.8$ V and 2.0 V for samples I and II, respectively. In the spin-injection experiment, the electroluminescence polarization depends on the spin-relaxation and electron-recombination times in the quantum-well detector. The measured luminescence polarization $P$ in a steady state is given [9] by

$$P = \frac{\tau_S}{\tau_S + \tau_R} P_0, \tag{4}$$

where $P_0$ is the initial spin polarization of the electrons after they relax to the quantum-well conduction band, and $\tau_S$ and $\tau_R$ are respectively the spin and electron lifetimes of the thermalized electrons. The DP spin-relaxation rate for thermalized electrons in a quantum well is

$$\tau_S^{-1} \propto \tau_p T, \tag{5}$$

where $\tau_p$ is the momentum-scattering time and $T$ is the temperature [46]. At very low temperatures, $\tau_p$ is dominated by ionized impurity scattering, which has a weak temperature dependence; hence, $\tau_p T$ and, consequently, the spin-relaxation rate increase with temperature. This gives rise to a decreased polarization. At higher temperatures, when polar optical phonon scattering dominates the momentum scattering, $\tau_p T$ and, therefore, the spin-relaxation rate decrease with increasing temperature [50]. As a result, the luminescence polarization tends to increase with temperature. Puller et al. have calculated the DP spin-relaxation rate in a quantum well [50]. They predicted that a maximum DP spin-relaxation rate exists in the intermediate-temperature range, which is qualitatively consistent with the experimental data shown in Figure 6. In addition to the temperature dependence of the spin-relaxation time, the electron recombination time in a quantum well also varies with temperature. It has been observed that the recombination time may increase with temperature in the low-temperature regime and then decrease with temperature in the high-temperature regime. From Equation (4), this could also lead to a non-monotonic temperature dependence of the polarization. Both the spin-relaxation rate and the electron recombination time are dependent on the details of the quantum well detectors, which likely accounts for the quantitative differences between samples I and II.

Note that the applied bias $V_T$ extends across the entire LED structure. As the temperature changes, the total voltage drop across the MgO barrier and the n-type or p-type AlGaAs depletion region ($V_I$) can vary slightly even if $V_T$ remains constant. However, changes in $V_I$ would give rise to a monotonic temperature dependence of the polarization and thus cannot account for the experimental results. In addition, current–voltage measurements suggested that the change of $V_I$ with temperature at a given $V_T$ was small and therefore could not significantly influence the temperature dependence of the electroluminescence polarization. Spin-relaxation mechanisms other than the DP mechanism, such as the EY and BAP mechanisms, cannot account for the increase of polarization with temperature. The EY spin-relaxation rate is proportional to the momentum-scattering rate and would, therefore, give rise to a decreased polarization with increasing temperature, while BAP relaxation is weak in undoped quantum wells and cannot give rise to the observed temperature dependence. Moreover, DP spin relaxation in bulk semiconductors has a rate proportional to $T^3$. Such relaxation in the GaAs and AlGaAs layers between the injector and the quantum well is unlikely to give rise to the pronounced non-monotonic temperature dependence which was observed.

The experimental results discussed so far were obtained after the samples were post-growth-annealed in a high-vacuum furnace at 300°C for one hour. It was found that the spin injection efficiency could be significantly improved by such a thermal treatment [37]. **Figure 7** shows the $P_C$ values for sample I measured at various temperatures with $V_T = 1.8$ V before (solid circles) and after post-growth annealing at 300°C (solid triangles), 340°C (open squares), and 400°C (crosses). The temperature dependence of $P_C$ after annealing closely resembled that before annealing. Annealing at 180°C, 220°C, and 260°C introduced negligible changes in the electroluminescence polarization (not shown). However, annealing at 300°C produced a pronounced increase in $P_C$ (by nearly 10%) for temperature above 70 K, although only a modest improvement in polarization was seen for measurements below 70 K. Further annealing up to 400°C resulted in marginal additional improvements in $P_C$ at all temperatures (see Figure 7).

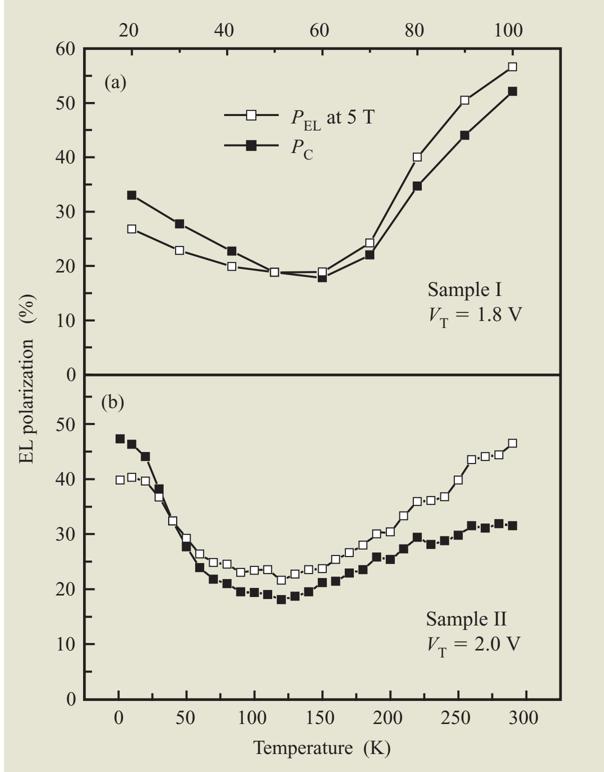



**Figure 6**

Temperature dependence of the electroluminescence polarization of (a) sample I and (b) sample II. Note the different temperature ranges for (a) and (b). Adapted from [36], with permission; ©2005 American Physical Society.

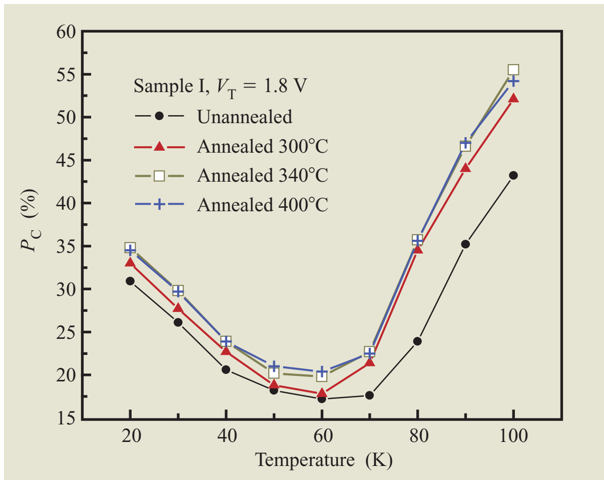



**Figure 7**

$P_C$ as a function of temperature for sample I before and after post-growth annealing at 300°C, 340°C, and 400°C. The bias voltage $V_T$ was 1.8 V. Adapted from [37], with permission.

Since the growth temperatures for the semiconductor heterostructure far exceeded the annealing temperatures used in these experiments, the quantum-well detector should not be affected by the annealing. Therefore, the increase in the electroluminescence polarization likely originated from an improvement of the CoFe/MgO/GaAs interfaces as well as the quality of the MgO tunnel barrier. Indeed, annealing treatments have been found to improve the tunneling spin polarization in CoFe/MgO-based tunnel junctions [35].

## Summary

Efficient spin injection of 57% at 100 K and 47% at 290 K was obtained using a CoFe/MgO spin injector. The observed large spin polarization up to room temperature was consistent with the high Curie temperature of CoFe and the weak temperature dependence of spin-dependent tunneling. The actual spin injection efficiency was inferred to be higher than that obtained from the polarization of the quantum-well electroluminescence because of spin relaxation in the quantum-well detector. Moreover, the spin relaxation was found to be strongly bias- and temperature-dependent, giving rise to a monotonic bias dependence and a non-monotonic temperature dependence of the luminescence polarization. The MgO-based spin injector can readily be fabricated by sputter deposition. In addition, the MgO tunnel barrier prevents intermixing of the ferromagnetic metal and the semiconductor, leading to improved device thermal stability. These desirable features make MgO-based tunnel spin injectors attractive for future semiconductor spintronic applications.

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