Electrical spin injection into semiconductors

D. L. Smith and R. N. Silver
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 13 September 2000; revised manuscript received 31 January 2001; published 2 July 2001)

We present the results of a theoretical model describing electrical spin injection from a spin-polarized contact into a nonmagnetic semiconductor. The model includes the possibility of interface resistance due, for example, to a tunnel barrier at the contact/semiconductor heterojunction, and shows that such interface resistance can be critical in determining spin injection properties. With no interface resistance spin injection is very weak for contacts with typical metallic resistivities. For higher bulk resistivity contacts, such as doped semiconductors, or for completely spin-polarized contacts, strong spin injection is possible without significant interface resistance. However the spin polarization must be extremely close to complete for contacts with metallic resistivities. A tunnel barrier with spin-dependent interface resistance can greatly enhance spin injection. An insulating tunnel barrier with a spin-polarized contact, and a ferromagnetic insulator tunnel barrier, both have spin-dependent interface resistance, and provide two promising approaches to achieve significant electrical spin injection. The model is consistent with a variety of experimental observations, identifies the basic physics problems that must be addressed to achieve a high degree of spin injection, and suggests systematic strategies to achieve strong spin injection.

DOI: 10.1103/PhysRevB.64.045323 PACS number(s): 73.50.−h, 73.40.Qv

I. INTRODUCTION

Traditional semiconductor devices are based on the control and manipulation of electronic charge. Recently, semiconductor devices based on the control and manipulation of electron spin were proposed.[1–3] For such devices it is necessary to controllably introduce a spin-polarized electron population into the semiconductor. Optical pumping with circularly polarized light has been used to do this, and long spin lifetimes and diffusion lengths have been reported.[4–7] These long spin lifetimes and diffusion lengths argue that spin-based semiconductor devices are a realistic possibility.

Spin-polarized optical injection in semiconductors has been clearly demonstrated, but electrical injection of spin-polarized current is important for practical spin-based semiconductor devices. One might expect that a ferromagnetic metal contact would allow spin-polarized electrical injection. Electrons in the ferromagnetic metal are spin polarized, and a polarized injection current might be expected to result from such a contact. To date, however, this approach has not proved successful in achieving strong electrical spin injection. Reported injection current spin polarizations using this approach have been of the order of 1% or less[8,9] and the report of even these small effects has been challenged.[10] Spin-polarized injection has been reported using spin-polarized degenerately doped semiconductor contacts. In some cases, semimagnetic semiconductors with large *g* factors were used as contacts, and were spin polarized by a large external magnetic field at low temperature.[11–14] In one case a GaMnAs contact, a *p*-type ferromagnetic semiconductor, was used.[15] Spin-polarized electron injection has also been reported using ferromagnetic metal scanning tunneling microscopy (STM) tips.[16,17]

A recent theoretical paper analyzed current flow through a ferromagnet/semiconductor/ferromagnet structure, with the spins in the two ferromagnetic contacts either aligned parallel or antiparallel.[18] Contacts with no interface resistance were considered. The current transport in the semiconductor was in a quantized two-dimensional electron gas. A very small difference in the calculated resistance for parallel and antiparallel contact spin alignments was reported. This result argues that the electrical spin injection from a ferromagnetic metal into a two-dimensional electron gas in a semiconductor is weak. Approaches to achieve strong electrical spin injection are not discussed.

Here we consider electron injection from a spin-polarized contact, which may be a ferromagnetic metal or a spin-polarized degenerately doped semiconductor, into a lightly doped nonmagnetic semiconductor. The electron states in the semiconductor are three dimensional, and satisfy nondegenerate statistics. We include the possibility of finite interface resistance due, for example, to a tunnel barrier at the contact/semiconductor heterojunction. We find very weak spin injection from a contact with truly metallic bulk conductivity and no interface resistance, in agreement with the results of Ref. 18 for injection into a quantized two-dimensional electron gas. If the bulk conductivity of the contact material is substantially below metallic values, conductivities that are more typical of a doped semiconductor contact, significant spin injection can be achieved without interface resistance. A tunnel barrier can significantly enhance spin injection if it has a spin-dependent interface resistance. An insulating tunnel barrier with a spin-polarized contact has spin-dependent resistance because of the difference in Fermi wave vectors for the two spin types in the contact material.[19] Indeed, spin-dependent tunneling resistance out of a ferromagnetic contact is the essential principle behind magnetic random access memory that employs metal/insulator/metal structures. A ferromagnetic insulator tunnel barrier can also have spin-dependent transmission properties. These are two examples of interface structures with spin-dependent resistance. They provide promising approaches to achieve significant electrical spin injection. An essential conclusion of this work is that effective spin injection into semiconductors can be achieved using spin-dependent tunneling. A half-metallic ferromagnetic contact, in which only electrons of one spin type occur at the Fermi surface, can also give strong spin injection without interface resistance. In this case, however, the spin polarization in a contacting material with metallic conductivity must be extremely close to complete for significant spin injection. The paper is organized in the following fashion: in Sec. II we describe the spin injection model, in Sec. III we present our numerical results, and in Sec. IV we summarize our conclusions.

II. SPIN INJECTION MODEL

We describe a spin-polarized contact/semiconductor structure using the transport model of Ref. 20, in which the drift-diffusion equations describe the current flow

$$j_\eta = \sigma_\eta \frac{\partial(\mu_\eta/e)}{\partial x}. \tag{1}$$

Here j_η is the current density due to electrons of spin type η, σ_η is the conductivity for electrons of that spin type, μ_η is the corresponding electrochemical potential, e is the magnitude of the electron charge, and x is the position. Equation (1) assumes rapid wave vector randomizing scattering events, so that electrons of the same spin stay in local quasithermal equilibrium. However, spin-flip scattering can be comparatively slow, so that electrons of different spin may be driven out of local quasithermal equilibrium with each other by, for example, an applied current density. The conductivities are, of course, different in the contact and the semiconductor.

If electrons with different spins are driven out of local quasithermal equilibrium, so that $\mu\uparrow$ is not equal to $\mu\downarrow$, at some point in space, the difference in the two electrochemical potentials relax as described by a diffusion equation

$$\frac{\partial^2(\mu\uparrow - \mu\downarrow)}{\partial x^2} = \frac{(\mu\uparrow - \mu\downarrow)}{\Lambda^2}. \tag{2}$$

Here Λ is a spin diffusion length, which is different in the contact and the semiconductor. At the contact/semiconductor interface, electrons of different spin can be driven out of quasithermal equilibrium by current flow. Far from the interface, located at $x=0$, $(\mu\uparrow - \mu\downarrow)$ returns to zero in both the contact and the semiconductor. The total steady-state current density is a constant function of position. We assume no strong spin-flip scattering at the interface, so that the individual current components for the two spin types are continuous at the interface. It is not difficult to include interfacial spin-flip scattering in the model, but it adds additional unknown parameters and further reduces the degree of spin injection.

Current flow at the interface is described using an interface conductance

$$j_\eta^0 = G_\eta(\Delta\mu_\eta/e) \tag{3}$$

where j_η^0 is the current density at the interface, G_η is the interface conductance ($1/G_\eta$ is the interface resistance), and $\Delta\mu_\eta$ is an interfacial discontinuity in electrochemical potential for electrons of spin type η. If the interface conductance is infinite, the electrochemical potential is continuous at the interface whereas for finite values of G_η a discontinuity in μ_η develops.

Because the steady state current is constant, it is convenient to define a variable β by $j\uparrow = \beta j$ where j is the total electron current density $[j\downarrow = (1-\beta)j]$. β is continuous at the interface. We take the electron density as a function of position to be fixed, independent of the current density j, by electrostatic constraints.[21] We take the conductivities for the two spin types in the semiconductor to be proportional to the corresponding electron densities with the same proportionality constant. The total conductivity is then fixed independent of current density. It is convenient to define a variable α by $\sigma\uparrow = \alpha\sigma$ where σ is the total conductivity $[\sigma\downarrow = (1-\alpha)\sigma]$. α is not continuous at the interface. Because the electron density is much greater in the contact than in the semiconductor, the fractional spin density can be more easily changed in the semiconductor than in the contact material. Therefore in the semiconductor, α_S is taken to be a function of current density and position; but in the contact, α_c is taken independent of current density and position.[22] (Subscript s and c will be used to refer to the semiconductor and contact, respectively.) We consider nondegenerate statistics in the semiconductor with the conductivity proportional to the electron density, so that

$$\alpha_s = \frac{n\uparrow_s}{n\downarrow_s + n\uparrow_s} = \frac{1}{(1+e^{-(\mu\uparrow-\mu\downarrow)/kT})}, \tag{4}$$

where $n_{\eta s}$ is the density of electrons with spin η in the semiconductor, k is Boltzmann's constant, and T is temperature.

We take the contact on the left and the semiconductor on the right-hand side of the interface, so that the current density j is negative for electron injection into the semiconductor. Solving Eq. (2) with the stated boundary conditions gives

$$(\mu\uparrow - \mu\downarrow) = Ae^{x/\Lambda_c}, \quad x<0, \tag{5a}$$

$$(\mu\uparrow - \mu\downarrow) = Be^{-x/\Lambda_s}, \quad x>0. \tag{5b}$$

Equation (3) for the interfacial discontinuity in electrochemical potential gives a relation between the coefficients A and B,

$$B - A = ej\left[\beta\left(\frac{1}{G\uparrow} + \frac{1}{G\downarrow}\right) - \frac{1}{G\downarrow}\right], \tag{6}$$

where β is evaluated at the interface. Drift-diffusion equations [like Eq. (1)], evaluated at the two sides of the interface, combine to give

$$\frac{ej}{\sigma_c}\left(\frac{\beta - \alpha_c}{\alpha_c(1-\alpha_c)}\right) = A/\Lambda_c \tag{7a}$$

and

$$\frac{ej}{\sigma_s}\left(\frac{\beta - \alpha_s}{\alpha_s(1-\alpha_s)}\right) = -B/\Lambda_s, \tag{7b}$$

where α_s and β are evaluated at the interface. Equations (6) and (7) can be solved to give the injected current spin polarization

$$\frac{j\uparrow - j\downarrow}{j\uparrow + j\downarrow} = (2\beta - 1) = \frac{(2\alpha_c - 1)R_c + (2\alpha_s - 1)R_s + (1/G\uparrow) - (1/G\downarrow)}{R_c + R_s + (1/G\uparrow) + (1/G\downarrow)}, \tag{8}$$

where position-dependent quantities are evaluated at the interface and

$$R = \frac{\Lambda}{\sigma\alpha(1-\alpha)}. \tag{9}$$

R_c and R_s for the contact and the semiconductor, respectively, are important parameters in the model. They correspond to the sum of the bulk resistivities for the two spin types (i.e., $[(1/\sigma\uparrow) + (1/\sigma\downarrow)]$) times the spin diffusion length. They have the units of interface resistance, $\Omega\,\mathrm{cm}^2$.

At very low current density there is no spin-density polarization in the semiconductor, and $\alpha_s = \frac{1}{2}$. But at larger current density, spin polarization of the electron density in the semiconductor can occur, and α_s can deviate from $\frac{1}{2}$. In this high current density regime α_s is found by solving Eq. (4) and

$$\alpha_s = \frac{\left(R_c G\downarrow + \dfrac{1}{\alpha_c}\right)\alpha_c}{\left(R_c G\downarrow + \dfrac{G\downarrow}{G\uparrow} + 1\right)} + \left\{ \frac{G\downarrow}{\left(R_c G\downarrow + \dfrac{G\downarrow}{G\uparrow} + 1\right)} + \frac{1}{R_s} \right\} \times \left(\frac{B}{ej}\right). \tag{10}$$

Equation (10) follows from Eqs. (6) and (7). Here B is $(\mu\uparrow - \mu\downarrow)$ evaluated at the semiconductor side of the interface. It is linear in j at small j.

Position dependences are determined once the interface quantities are found:

$$\beta(x) = \alpha_c + \frac{1}{R_c}\left(\frac{A}{ej}\right)e^{x/\Lambda_c}, \quad x<0, \tag{11a}$$

$$\beta(x) = \alpha_s(x) - \frac{1}{R_s(x)}\left(\frac{B}{ej}\right)e^{-x/\Lambda_s}, \quad x>0. \tag{11b}$$

The position dependence of $\alpha_s(x)$ and $R_s(x)$ follows from Eqs. (4), (5), and (9). The position dependence of the chemical potentials can be found by integrating Eq. (11) in space, using Eq. (1),

$$\mu\uparrow = \frac{ej}{\sigma_c}x + A(1-\alpha_c)(e^{x/\Lambda_c} - 1), \quad x<0, \tag{12a}$$

$$\mu\uparrow = \frac{ej}{\sigma_s}x + B(e^{-x/\Lambda_s} - 1) + \frac{B}{\Lambda_s}\int_0^x \alpha_s(x)e^{-x/\Lambda_s}dx + \mu_\uparrow^+, \quad x>0, \tag{12b}$$

where $\mu\uparrow$ in the contact at the interface is set to zero as an arbitrary zero of energy, and $\mu_\uparrow^+$ is the discontinuity in $\mu\uparrow$ at the interface which is found from Eq. (3). The position dependence of $\mu\downarrow$ is found from Eqs. (5) and (12).

III. NUMERICAL RESULTS

At thermal equilibrium for these structures, electron spins are polarized in the contact but not in the semiconductor. To achieve spin injection, the system must be driven out of equilibrium by an electric current in such a way that the electrons injected into the semiconductor are spin polarized. There is a fundamental difference in how spin polarization is maintained in the contact as compared with the semiconductor. The contact maintains a spin polarization due to different densities of states for spin-up and -down electrons. It does not require a splitting in the electrochemical potential for different spin types. By contrast, the semiconductor has the same density of states for spin-up and -down electrons, so a splitting of the electrochemical potentials for the spin types is required for spin polarization. Because the electron density and therefore the electrical conductivity are high in the contact material, and also because the spin diffusion length is comparatively short in the contact, it is difficult to drive the electron population in the contact far from local quasithermal equilibrium with a physically attainable current density. If the bulk contact is truly metallic, this is essentially impossible. At a spin-polarized contact/semiconductor heterojunction with no interface resistance, the electrons in the contact and in the semiconductor are in good thermal contact, and therefore they stay in local equilibrium with each other. Since the electrons in the contact stay near local quasithermal equilibrium, so do those in the semiconductor, with the result that strong spin injection is difficult to achieve. This is the essential physical problem in achieving strong electrical spin injection. The behavior is described by Eq. (8), which gives the injection current spin polarization. At low current density, $\alpha_s = \frac{1}{2}$ and $\alpha_c > \frac{1}{2}$. (We take the dominant spin type as spin-up.) The conductivity of the contact is typically much larger than that of the semiconductor, and the spin diffusion length of the semiconductor is typically larger than that of the contact, so that typically $R_s \gg R_c$. If the interface resistance is small so that the terms involving $1/G_\eta$ can be neglected, the injected current spin polarization is small at low current density. From Eqs. (4) and (10), we see that α_s at the interface increases to α_c, for small interface resistance, at sufficiently large current density. At such large current densities, the injection current spin polarization becomes $(2\alpha_c - 1)$—that is, the spin polarization of the contact, which can be a large value. However, the values of current density required to achieve this condition are unphysically large for truly metallic contacts. If the interface resistance is large, electrons on the two sides of the interface are not in good thermal contact with one another. Thus it is possible for the spin populations on the semiconductor side of the interface to be out of local quasithermal equilibrium, even though those on the contact side are in local quasithermal equilibrium. This situation is described by Eq. (8), when the interface conductance terms dominate the bulk terms containing the R parameters. Strong spin injection can be achieved in this case if the interface resistances for the two spin types differ significantly.

If an electrical bias is applied to a spin-polarized contact/semiconductor structure, the current in the contact far from the interface is predominantly from the electron-spin type with the larger density of states at the Fermi surface. At first it might seem that the current density would continue to be dominated by electrons of this spin type up to the interface, and that strong spin injection would result. This is usually not the case, however. If the interface resistance is small, the electrons on the two sides of the interface remain in local equilibrium. For a high conductivity contact, it is easy to change the ratio of current carried by the two spin types, within a spin diffusion length of the interface, by having a larger gradient in electrochemical potential for the minority-spin type. The ratio of the gradients in electrochemical potentials for the two spin types determines the ratio of current carried by the two spin types. For a highly conductive ferromagnetic metal, the absolute magnitudes of the electron electrochemical potential gradients are very small. However, there is nothing to prevent the ratio of the gradients for the two spin types from being significantly different from unity, within a spin diffusion length of the interface, even though both gradients are small in absolute value. Since it is the ratio of the gradients in electrochemical potentials that determines the ratio of current carried by the two spin types, this ratio can vary within a spin diffusion length of the interface, so that current in the contact near the interface is no longer strongly spin polarized. Because, in the contact, the absolute value of the chemical-potential gradients is small and the spin diffusion length is comparatively short, the separation in electrochemical potentials for the two spin types at the interface remains small.

The point is illustrated in Fig. 1, which shows a calculation of the current spin polarization, defined as $(j\uparrow - j\downarrow)/(j\uparrow + j\downarrow)$, as a function of position. The calculation is for zero interface resistance, a current density of 1 A/cm^2, 80% spin polarization in the contact (i.e., $\alpha_c = 0.9$), so that deep in the bulk of the contact $J\uparrow$ is nine times larger than $J\downarrow$, and a contact spin diffusion length of 100 nm (these values for the spin polarization and spin diffusion length of the contact are used throughout the paper) at room temperature. The semiconductor spin diffusion length is 1 μm, and its resistivity is 1 Ω cm. (These values for the semiconductor parameters are fixed throughout the paper.) The bulk resistivity of the contact is varied in Fig. 1. For a low bulk resistivity contact, a larger electrochemical gradient develops within a spin diffusion length of the interface for spin-down electrons, and the currents due to the two spin types approach each other near the interface. As a result the spin injection is weak. As the resistivity of the contact material is increased, it becomes possible to drive the higher resistivity contact material further out of quasithermal equilibrium, and more significant spin injection can occur. The contact resistivities used in the calculations for Fig. 1 are all significantly larger than typical metallic values. For true metallic resistivities the spin polarization current is very small at the interface.

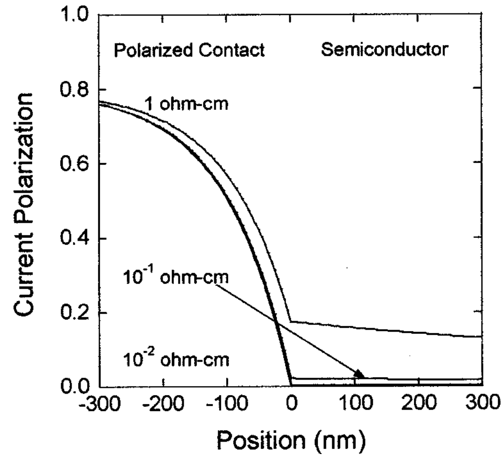

FIG. 1. Calculated current spin polarization at room temperature as a function of position near a spin-polarized contact/semiconductor interface with no interface resistance for various values of the bulk resistivity of the contact material.

If a tunnel barrier with different resistances for the two spin types is introduced at the contact/semiconductor interface, strong spin injection can result. Figure 2 shows a calculation of the current spin polarization as a function of position for a metallic bulk contact resistivity of $10^{-5}\,\Omega$ cm and a current density of 1 A/cm^2 at room temperature. The interface resistance for spin-up electrons is one-tenth that of spin-down electrons, and the interface resistance of spin-down electrons is varied. When an interface with spin-selective resistance is included, a discontinuity in the electrochemical potential difference that enhances spin injection develops at the interface, because the spin-up electrons have

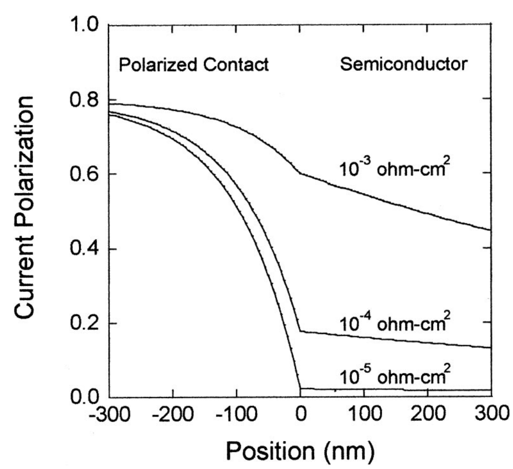

FIG. 2. Calculated current spin polarization at room temperature as a function of position near a spin-polarized contact/semiconductor interface with a spin-selective interface resistance, and the metallic bulk resistivity of the contact material for various values of the spin-down interface resistance.

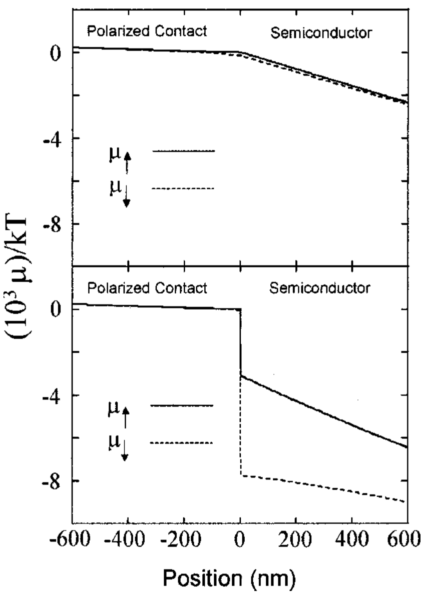

FIG. 3. Calculated position dependence of spin-up (solid lines) and spin-down (dashed lines) electron electrochemical potentials for a bulk contact resistivity of $10^{-1}\ \Omega$ cm with zero interface resistance (upper panel), and with a spin-down electron interface resistance of $10^{-3}\ \Omega\ \mathrm{cm}^2$ and a spin-up electron interface resistance a tenth of the spin-down value (lower panel) at a current density of 1 A/cm^2 at room temperature.

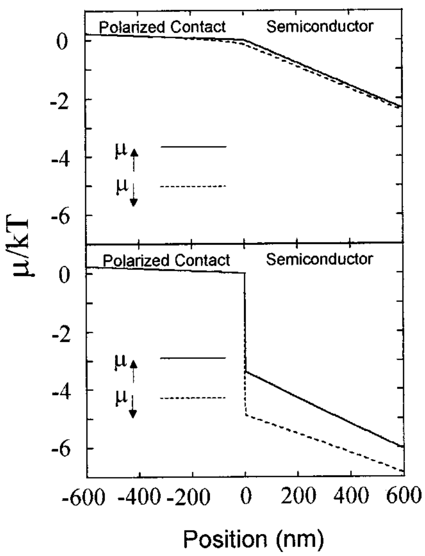

FIG. 4. Calculated position dependence of spin-up (solid lines) and spin-down (dashed lines) electron electrochemical potentials for the same material parameters as in Fig. 3) at a current density of 10^3 A/cm^2 at room temperature.

a smaller interface resistance. The discontinuity that occurs at a spin-selective interface is a promising approach with which to obtain a significant difference in electrochemical potentials at the semiconductor side of the interface, and therefore significant spin injection. However, if the interface resistance is spin independent, there is a discontinuity in the electrochemical potential difference at that interface, with a sign that reduces spin injection because the current for spin-up electrons is larger than for spin-down electrons, and therefore the interfacial drop in electrochemical potential is larger for spin-up electrons, leading to a reduction in spin injection.

Figure 3 shows the calculated position dependence of the spin-up (solid lines) and spin-down (dashed lines) electron electrochemical potentials for a bulk contact resistivity of $10^{-1}\ \Omega$ cm, with zero interface resistance for both spin-type electrons (upper panel) and with a spin-down electron interface resistance of $10^{-3}\ \Omega\ \mathrm{cm}^2$ and a spin-up electron interface resistance one-tenth of the spin-down value (lower panel) at a current density of 1 A/cm^2 at room temperature. Figure 4 shows the calculated electrochemical potentials at room temperature as a function of position for the same material parameters at a current density of 10^3 A/cm^2. For cases without contact resistance, the electrochemical potentials are continuous at the interface. A slightly greater gradient develops in the spin-down electron electrochemical potential than in the spin-up potential, and the currents for the two spin types become nearly equal at the interface (compare with Fig. 1). Even for the comparatively large current density of 10^3 A/cm^2, the spin injection is quite small. For true metallic values for the contact resistivity, the separation between the spin-up and -down electron electrochemical potentials cannot be seen on the scale of Fig. 3. For the case with a spin-selective interface resistance, there is a discontinuity in the electrochemical potentials at the interface. A separation in these potentials occurs because of the different interface resistivities. For a 1-A/cm^2 current density the injection current is strongly spin polarized (compare with Fig. 2), but the magnitude of the injected current is not large enough to effectively polarize the electrons already in the semiconductor. This is indicated by the fact that the separation between the spin-up and -down electrochemical potentials is small compared to kT. For a 10^3-A/cm^2 current density, the injection current is also strongly spin polarized, and the magnitude of the injected current is large enough to effectively polarize the electrons in the semiconductor, as indicated by the fact that the separation between the spin-up and -down electrochemical potentials is larger than kT.

The upper panel of Fig. 5 shows the room-temperature injection current spin polarization as a function of current density for zero interface resistance and various bulk contact resistivities. For high conductivity contacts, a larger electrochemical gradient develops within a spin diffusion length of the interface for spin-down electrons, and the currents due to the two spin types of electrons become nearly equal at the interface. As a result the spin injection is weak. For lower conductivity contacts it is easier to drive the contact out of quasithermal equilibrium, and the spin injection is stronger. The lower panel in Fig. 5 shows the calculated spin density, defined as $(2\alpha_s-1)=(n_s\uparrow-n_s\downarrow)/(n_s\uparrow+n_s\downarrow)$, in the semiconductor at the interface as a function of current density. Compare with the upper panels of Figs. 3 and 4, which show the corresponding electrochemical potentials. In this structure the injected electrons are not confined close to the interface in the semiconductor by, for example a quantum well, and fairly high current densities are required to achieve a strong density polarization even when the injection current is

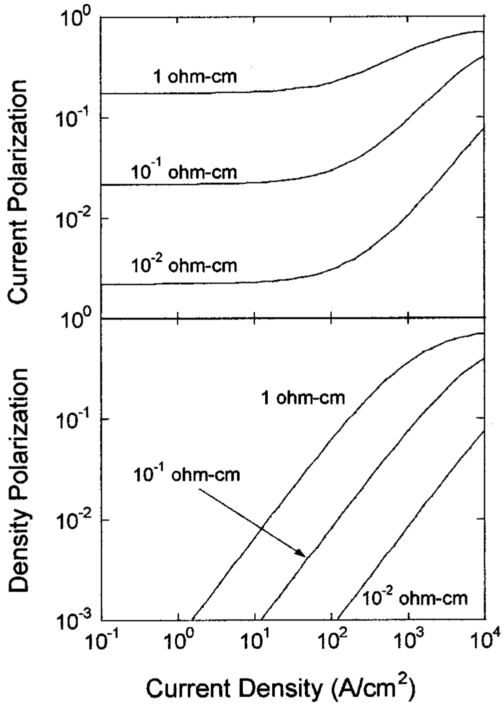

FIG. 5. Calculated injection current spin polarization (upper panel) and electron density spin polarization (lower panel) at room temperature as a function of current density at a spin-polarized contact/semiconductor interface with no interface resistance, for various values of the bulk resistivity of the contact material.

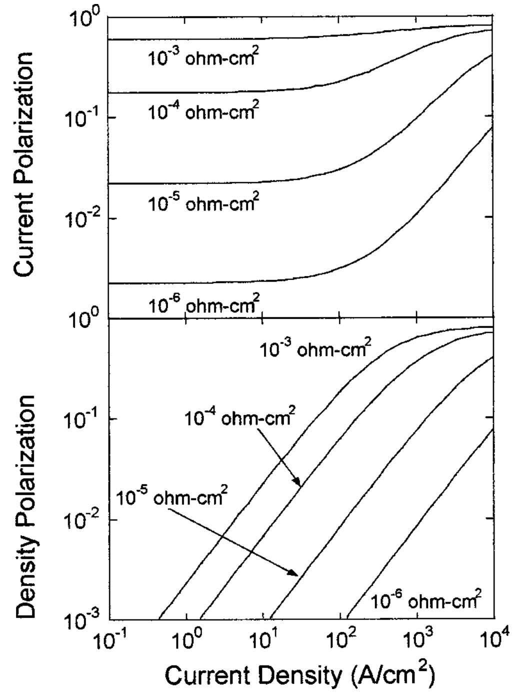

FIG. 6. Calculated injection current spin polarization (upper panel) and electron density spin polarization (lower panel) at room temperature as a function of current density for a spin-polarized contact/semiconductor interface with a spin-selective interface resistance, and the metallic bulk resistivity of the contact material for various values of the spin-down interface resistance.

strongly polarized. For semiconductor structures in which the injected electrons are confined near the interface, strong density polarization can be achieved at lower current densities.

The upper panel of Fig. 6 shows the calculated room temperature injection current polarization as a function of current density for varying interface resistance for the spin-down electrons. The calculation is for a contact with a metallic bulk resistivity ($10^{-5}\,\Omega$ cm) at room temperature. The spin-up electrons have one-tenth of the spin-down electron interface resistance. Electrons on the two sides of the interface do not remain in local equilibrium with each other because of the interface resistance. Spin injection is reduced as the interface resistance is reduced. The lower panel in Fig. 6 shows the calculated spin density in the semiconductor near the interface as a function of current density. Compare with the lower panels of Figs. 3 and 4, which show the corresponding electrochemical potentials. The injected electrons are not confined in the semiconductor in this structure, and fairly high current densities are required to achieve a strong density polarization even when the injection current is strongly polarized.

Figure 7 shows the calculated injection current spin polarization as a function of current density for a low interface resistance with varying bulk contact resistivities (upper panel); and for a metallic ($10^{-5}\,\Omega$ cm) bulk contact resistivity with varying spin-down interface resistances the (spin-up interface resistance is fixed at one-tenth of the spin-down value) at 4 K. Comparing with Figs. 5(a) and 6(a), which show the same calculations for room temperature, we see

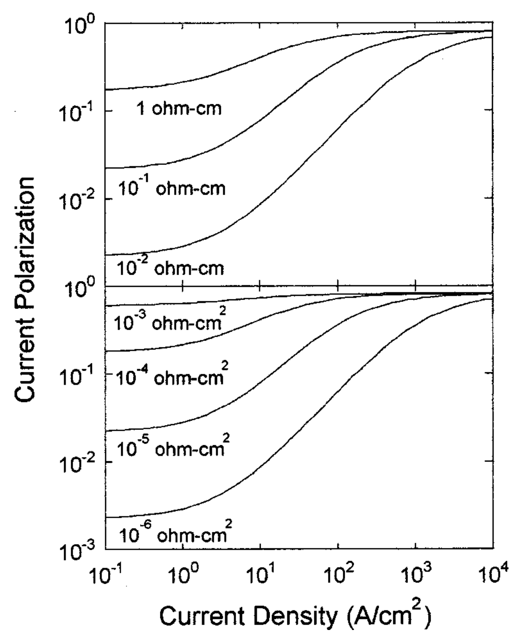

FIG. 7. Calculated injection current spin polarization at 4 K as a function of the current density for a spin-polarized contact/semiconductor interface with no interface resistance for various values of the bulk resistivity of the contact material (upper panel); and a spin-selective interface resistance and metallic bulk resistivity of the contact material for various values of the spin-down interface resistance (lower panel).

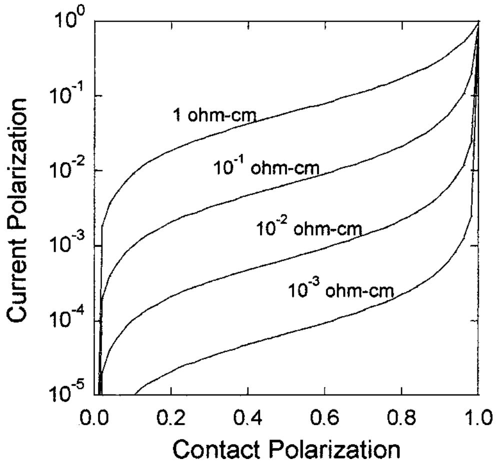

FIG. 8. Calculated injection current spin polarization at room temperature as a function of contact spin polarization for a spin-polarized contact/semiconductor interface with no interface resistance, for various values of the bulk resistivity of the contact material.

that the low current density results do not depend explicitly on temperature (except through the values of the material parameters which normally would change with temperature), but that the value of the current density at which the degree of spin injection begins to increase moves to lower values with decreasing temperature. This explicit temperature dependence arises from the temperature dependence of α_s in Eq. (4).

If the contact is completely spin polarized, so that there are only electrons of one spin type at the Fermi surface $(\alpha_c = 1)$, the injected electron current will be completely spin polarized. This can be seen from Eqs. (8) and (9). However, for high bulk conductivity, contacts with no interface resistance the spin polarization of the contact must be extremely close to complete for this result to follow. This point is emphasized in Fig. 8, in which the calculated injection current spin polarization is plotted as a function of contact spin polarization, defined as $(2\alpha_c - 1)$, for various bulk contact resistivities with no interface resistance at room temperature. For zero contact spin polarization there is, of course, no spin injection, and for complete contact spin polarization the injected current is completely spin polarized independent of the bulk contact resistivity. However, for conductive bulk contacts the spin injection drops off extremely rapidly for very small deviations from complete contact spin polarization.

IV. SUMMARY AND CONCLUSION

We presented results of a theoretical model describing electrical spin injection from a spin-polarized contact into a nonmagnetic semiconductor. The model includes the possibility of interface resistance due, for example, to a tunnel barrier at the contact/semiconductor heterojunction, and shows that such interface resistance can be critical in determining spin injection properties. Without a tunnel barrier spin injection is very weak for metallic ferromagnetic contacts. At thermal equilibrium, electron spins are polarized in the contact but not in the semiconductor. To achieve spin injection, the system must be driven out of equilibrium by an electric current, in such a way that the electrons injected into the semiconductor are spin polarized. It is difficult to drive the electron population in a metallic contact far from local quasithermal equilibrium with a physically attainable current density because of its high electrical conductivity and comparatively short spin diffusion length. For a spin-polarized contact/semiconductor heterojunction with no interface resistance, the electrons in the contact and in the semiconductor are in good thermal contact, and therefore the electrons in the semiconductor also stay in local quasithermal equilibrium. As a result spin injection is weak. This is the essential physical problem in achieving strong electrical spin injection. To achieve strong spin injection it is necessary to provide a mechanism that allows the applied current density to drive electrons out of quasithermal equilibrium either in the bulk contact or at the contact/semiconductor interface; that is, a mechanism to allow hot electron injection must be provided. A tunnel barrier with spin-dependent resistance provides such a mechanism and can significantly enhance spin injection. An insulating tunnel barrier with a spin-polarized contact has spin-dependent interface resistance because of the difference in Fermi wave vectors for the two spin types in the contact material. A ferromagnetic insulator tunnel barrier can also have spin-dependent interface resistance. These interface structures with spin-dependent interface resistance provide promising approaches to achieve significant spin injection. A main conclusion of this work is that spin-dependent tunneling can be employed to achieve effective spin injection into semiconductors. For higher bulk resistivity contacts, such as doped semiconductors, or for completely spin-polarized contacts, strong spin injection is possible without a tunnel barrier. However, the spin polarization must be extremely close to complete for metallic contacts. The theory is consistent with a variety of experimental observations. It explains why strong spin injection has been difficult to achieve from metallic ferromagnetic contacts that have high bulk conductivity, but for spin-polarized semiconductor contacts with much lower bulk conductivity significant spin injection has been observed. Significant spin injection can occur using metallic ferromagnetic STM tips because of the vacuum tunnel barrier present in the STM structure.

ACKNOWLEDGMENTS

This work was supported by the Los Alamos National Laboratory LDRD program. We thank J. N. Schulman, I. H. Campbell, and T. C. McGill for valuable comments and suggestions.

[1] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
[2] S. Gardelis, C. G. Smith, C. H. W. Barnes, E. H. Linfield, and D. A. Ritchie, Phys. Rev. B **60**, 7764 (1999).
[3] G. A. Prinz, Science **282**, 1660 (1998).
[4] J. M. Kikkawa, D. D. Awschalom, I. P. Smorchkova, and N. Samarth, Science **277**, 1284 (1997).
[5] J. M. Kikkawa and D. D. Awschalom, Phys. Rev. Lett. **80**, 4314 (1998).
[6] J. M. Kikkawa and D. D. Awschalom, Nature (London) **397**, 139 (1999).
[7] D. Hägele, M. Oestreich, W. W. Rühle, N. Nestle, and K. Eberl, Appl. Phys. Lett. **73**, 1580 (1998).
[8] Y. Q. Jia, R. C. Shi, and S. Y. Chou, IEEE Trans. Magn. **32**, 4707 (1996).
[9] P. Hammer, B. R. Bennett, M. J. Yang, and M. Johnson, Phys. Rev. Lett. **83**, 203 (1999).
[10] F. G. Monzon, H. X. Tang, and M. L. Roukes, Phys. Rev. Lett. **84**, 5022 (2000); B. J. van Wees, *ibid.* **84** , 5023 (2000); and the reply by P. Hammer, B. R. Bennett, M. J. Yang, and M. Johnson, *ibid.* **84**, 5024 (2000).
[11] R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag, and L. W. Molenkamp, Nature (London) **402**, 787 (1999).
[12] G. Schmidt, R. Fiederling, M. Keim, G. Reuscher, T. Gruber, W. Ossau, A. Waag, and L. W. Molenkamp, Superlattices Microstruct. **27**, 297 (2000).
[13] M. Oestereich, J. Hubner, D. Hägele, P. J. Klar, W. Heimbrodt, W. W. Rühle, D. E. Ashenford, and B. Lunn, Appl. Phys. Lett. **74**, 1251 (1999).
[14] B. T. Jonker, Y. D. Park, B. R. Bennett, H.-D. Cheong, G. Kioseoglou, and A. Petrou, Phys. Rev. B **62**, 8180 (2000).
[15] Y. Ohno, D. K. Young, B. Beschoten, F. Matsukura, H. Ohno, and D. D. Awschalom, Nature (London) **402**, 790 (1999).
[16] S. F. Alvardo and P. Renaud, Phys. Rev. Lett. **68**, 1387 (1992).
[17] S. F. Alvardo, Phys. Rev. Lett. **75**, 513 (1995).
[18] G. Schmidt, D. Ferrand, L. W. Molenkamp, A. T. Filip, and B. J. van Wees, Phys. Rev. B **62**, R4790 (2000).
[19] See, for example, Y. Qi, Y. Xing, and J. Dong, Phys. Rev. B **58**, 2783 (1998).
[20] P. C. van Son, H. van Kempen, and P. Wyder, Phys. Rev. Lett. **58**, 2271 (1987).
[21] A specific device configuration must be specified to address the effects of possible interface charging on spin injection. Charging effects cannot influence the low current density spin injection results.
[22] The current density dependence of α_s and α_c cannot influence the low current density spin injection results. Since the electron density in the contact is much larger than that in the semiconductor, the spin polarization of the semiconductor is the dominant contribution to changes in spin injection at a high current density.