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There is significant current interest in spintronic devices fashioned after a spin analog of the electro-optic modulator proposed by Datta and Das [Appl. Phys. Lett. **56**, 665 (1990)]. In their modulator, the "modulation" of the spin-polarized current is carried out by tuning the Rashba spin-orbit interaction with a gate voltage. Here, we propose an analogous modulator where the modulation is carried out by tuning the Dresselhaus spin-orbit interaction instead, using a split gate. Additionally, the magnetization of the source and drain contacts in our device is *transverse* to the channel, whereas in the Datta-Das device, it is *along* the channel. Therefore, in the present modulator, there is no magnetic field in the channel unlike in the case of the Datta-Das modulator. This can considerably enhance modulator performance. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1790038]

In 1990, Datta and Das proposed a spintronic analog of the electro-optic modulator.[1] It consists of a quasi-one-dimensional semiconductor channel with ferromagnetic source and drain contacts [Fig. 1(a)]. Electrons are injected with a definite spin orientation from the source, which is then controllably precessed in the channel with a gate-controlled Rashba spin-orbit interaction,[2] and finally sensed at the drain. At the drain end, the electron's transmission probability depends on the relative alignment of its spin with the drain's (fixed) magnetization. By controlling the angle of spin precession in the channel with a gate voltage, one can control the relative spin alignment at the drain end, and hence control the source-to-drain current. This realizes the basic "transistor" action. Because of this attribute, the Datta-Das device came to be known as the ballistic spin field effect transistor (SPINFET).

Despite the fact that the SPINFET was proposed more than a decade ago, it has never been experimentally realized. Recently, we found that one of the serious impediments to its realization is the presence of a magnetic field in its channel caused by the ferromagnetic source and drain contacts. This field has been ignored in practically all past work, but has crucial consequences. Based on available data for device configurations that are similar to the SPINFET,[3] we estimate that in a 0.2 μm long channel, the average magnetic field may approach 1 T. This field has many deleterious effects.[4,5] First, it results in a Zeeman spin splitting that affects the dispersion relations of the Rashba spin split subbands in the channel. Consequently, there is "spin mixing" in each subband, so that no subband has a definite spin quantization axis.[4] As a result, nonmagnetic scatterers can flip spin,[5] thereby making spin transport nonballistic in the presence of normal impurities, surface roughness, etc., which otherwise would not have affected spin transport. Second, the "phase shift" of the spintronic modulator will be no longer independent of energy[4,5] (in Ref. 1, it was claimed to be independent of energy because the channel magnetic field was ignored). Therefore, ensemble averaging over electron energy will dilute the modulation effect. Suffice it to say then that it is important to eliminate the magnetic field in the channel.

Although it is possible to engineer the Datta-Das device to reduce the channel magnetic field, this field can never be completely eliminated (unless complicated spin filter devices[6] are employed). The only other solution is to find an alternate analogous device where the magnetic fields due to the source and drain contacts are *transverse* to the channel. Here, we do precisely that and propose an alternate device, based on the Dresselhaus spin-orbit interaction[7] rather than the Rashba interaction. In this device, the source-drain magnetization will be *transverse* to the channel, which vastly reduces the channel magnetic field. The only channel field that could be present is the fringing field at the edges adjoining the source and drain contacts. This is negligible.

Our device is schematically shown in Figs. 1(b) and 1(c). The one-dimensional (1D) channel is along the [100] crystallographic direction (assume a cubic crystal such as GaAs). Since the device has no *structural* inversion asymmetry, we can ignore the Rashba interaction. However, there is a bulk inversion asymmetry in the channel material that ensures the presence of a Dresselhaus interaction. The channel is strictly 1D (only the lowest subband is occupied by carriers) in order to extract the best device performance. The need for one dimensionality was already elucidated in Ref. 1. Furthermore, since there is no Dyakonov-Perel' spin relaxation in a strictly 1D channel *in the absence of a channel magnetic field*,[8] we can expect nearly ballistic spin transport in the present device for reasonable channel lengths. Following usual procedure, the 1D channel will be defined by split gates[9–11] on the surface of a quantum well heterostructure.

The single-particle Hamiltonian describing an electron in the 1D channel of this device is

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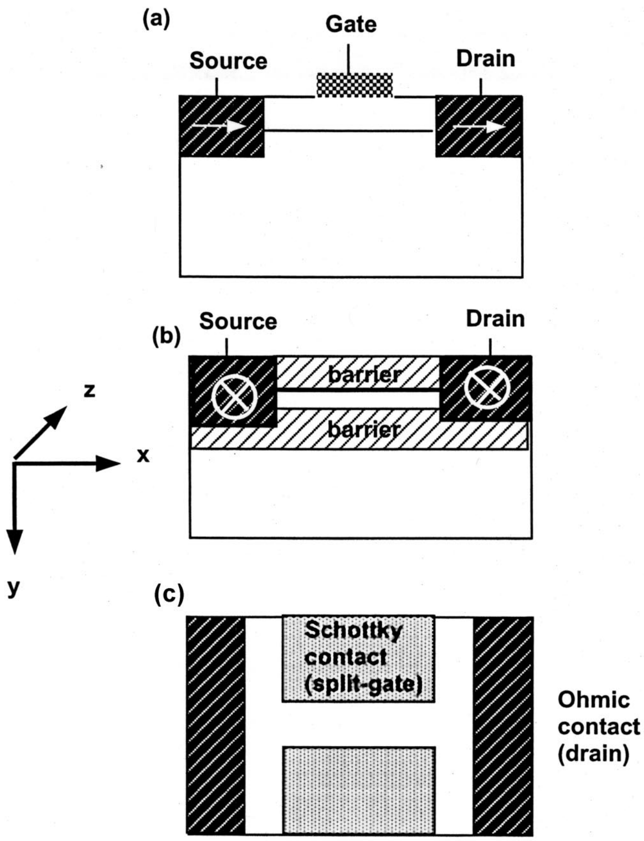

FIG. 1. (a) Schematic of the spintronic modulator of Ref. 1. (b) Side view of the spintronic modulator proposed in this work. (c) top view showing the split gates.

$$H = \varepsilon + \frac{\hbar^2 k_x^2}{2m^*} + 2a_{42}\sigma_x k_x\left[\frac{m^*\omega}{2\hbar} - \left(\frac{\pi}{W_y}\right)^2\right], \quad (1)$$

where ε is the lowest subband energy, a_{42} is the material constant associated with the strength of the Dresselhaus interaction,[12] σ is the Pauli spin matrix, and W_y is the channel dimension in the y direction. We assume the potential profile in the y direction to be a square well with hardwall boundaries [see Fig. 1(b)] and the potential profile in the z direction is parabolic since confinement in this direction is enforced by split gates. The curvature of the parabolic potential is ω, which can be tuned by varying the applied voltage on the Schottky split gates. Thus, by varying the split-gate voltage, we can tune the Dresselhaus interaction. This, in turn, results in a conductance modulation, as explained in the rest of this letter.

In this work, we have assumed a direct-gap semiconductor. The Dresselhaus spin-orbit interaction term has a subtle dependence on the crystallographic orientation of the channel,[13] but it is not *qualitatively* important in the present context. It may however assume importance in device optimization.

The rest of the analysis is fashioned after Ref. 1. Diagonalizing the Hamiltonian in Eq. (1), we find that the eigenspinors in the channel are $[1,1]^\dagger$ and $[1,-1]^\dagger$ which are $+x$-polarized and $-x$-polarized states. They have eigenenergies that differ by $2\beta k_x$, where $\beta = 2a_{42}[m^*\omega/(2\hbar) - (\pi/W_y)^2]$. Accordingly,

$$E(+x\ pol.) = \varepsilon + \hbar^2 k_{x+}^2/2m^* + \beta k_{x+},$$

$$E(-x\ pol.) = \varepsilon + \hbar^2 k_{x-}^2/2m^* - \beta k_{x-}. \quad (2)$$

An electron incident on the channel with energy E will have two different wave vectors k_{x+} or k_{x-} if its spin were either $+x$ or $-x$ polarized. Now, if we inject only $+z$-polarized electrons into the channel from a spin-polarized ferromagnetic source contact, the electron will couple equally to the $+x$- and $-x$-polarized subbands since

$$\begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}1\\1\end{bmatrix} + \begin{bmatrix}1\\-1\end{bmatrix}. \quad (3)$$

At the drain end, the eigenspinor will be $[e^{ik_{x+}L} + e^{ik_{x-}L}, e^{ik_{x+}L} - e^{ik_{x-}L}]^\dagger$, where L is the channel length. If the drain is a ferromagnet magnetized in the $+z$ direction, then the transmission probability of the electron (and therefore the linear response source to drain conductance) will be proportional to $|[1,0][e^{ik_{x+}L}+e^{ik_{x-}L}, e^{ik_{x+}L}-e^{ik_{x-}L}]^\dagger|^2 = 4\cos^2[(k_{x-} - k_{x+})L/2] = 4\cos^2[m^*\beta L/\hbar^2]$, where we have used Eq. (2) to arrive at the last equality. We can modulate the quantity β by changing the curvature of the confining potential ω along the z direction, with the split-gate voltage. This will change the phase shift $\phi(=2m^*\beta L/\hbar^2)$ between the two orthogonal spin states ($+x$ and $-x$ polarized), thereby changing the interference condition between them and resulting in a modulation of the source-to-drain conductance. Once we are able to modulate the source-to-drain conductance by changing the split-gate voltage, we have realized basic "transistor" action.

It is obvious now that this device is an exact analog of the device in Ref. 1. We point out that just as in Ref. 1, the phase shift ϕ is independent of the electron wave vector (or energy). In fact, it is more true of this device than the Datta-Das device, since there is no channel magnetic field here, and the channel magnetic field could make the phase shift slightly energy dependent.[5] Therefore, the interference between the two spin states causing the conductance modulation survives ensemble averaging over the electron energy at elevated temperatures. As a result, this device could operate at reasonably elevated temperatures like the Datta-Das device.

There are two basic differences between this and the Datta-Das device. First, the latter requires a "top gate" as shown in Fig. 1(a), whereas this requires a "split gate" as shown in Fig. 1(c). Second, and more importantly, the contacts in the present device have to be magnetized in the z direction (since we need to inject and detect $+z$ polarized electrons), whereas in the Datta-Das device, they are magnetized in the x direction. As a result, there is no significant channel magnetic field here, unlike in the Datta-Das device. Eliminating the channel magnetic field is a major advantage.

Before concluding this letter, we estimate by how much we need to constrict the channel with the split gate in order to change the phase shift between the two spin states by π radians (this corresponds to turning the device from "on" to "off," or vice versa). In other words, we need to estimate the change $\Delta(\hbar\omega)$, caused by the split-gate voltage, that will induce a phase shift of π radians. This value is given by $\hbar^4\pi/(2m^{*2}La_{42})$. In GaAs, $a_{42} \approx 2.9\times10^{-29}$ eV m^3.[12] Therefore, $\Delta(\hbar\omega) = 6.83$ meV if we assume the material to be GaAs and the channel length L to be 10 μm. As long as this value is smaller than $\hbar\omega$, we can turn the device on and off while maintaining "single modedness," meaning that at no time is more than one subband occupied by carriers. In split-gate channels fashioned out of GaAs, subband separation $\hbar\omega$ of 10 meV has been demonstrated.[11] Since $\Delta(\hbar\omega) < 10$ meV, we can switch the device from one state to another without ever impairing single modedness.

Next, we compare the switching voltages required to switch the Datta-Das modulator and the present modulator from one conductance state to another. In the Datta-Das modulator, a voltage is applied to a top gate to change the strength of the Rashba interaction parameter η,[1] whereas here a voltage is applied to a split gate to change the strength of the Dresselhaus interaction parameter β. The change $\Delta\eta$ required to induce a phase shift of π radians$=\pi\hbar^2/(2m^*L) = 1.7\times10^{-13}$ eV m for a 10-μm-long GaAs channel. Although no experimental data is available for Rashba effect in GaAs channels, experiments on InAs channels have revealed that η changes by approximately 1×10^{-12} eV m for every 1 volt change in gate voltage.[14] In GaAs channels, the Rashba effect is weaker than in InAs, so that the above would be a generous estimate for GaAs. Therefore the gate voltage (or switching voltage) required to switch a Datta-Das modulator of 10 μm channel length is $\approx$170 mV. In comparison, data in Ref. 11 reveals that we can change $\hbar\omega$ in a GaAs split-gate device by the required 6.83 mV with a gate voltage swing of $\approx$70 mV. Therefore, everything else being equal, the present modulator could have a smaller switching voltage than the Datta-Das device, which would result in a lower dynamic power dissipation during switching.

In conclusion, we have proposed a device which is analogous to the spintronic modulator proposed in Ref. 1, but has the advantage of having no channel magnetic field that causes a number of deleterious effects. Furthermore, this device could have a smaller switching voltage than the device of Ref. 1, resulting in lower power dissipation during switching. The fabrication of this device is no more difficult than fabricating the 1D modulator of Ref. 1; in fact, it may be somewhat simpler since we do not need a top gate (or back gate) to induce the Rashba effect. We emphasize that we make no claim whatsoever that this device will outpace conventional state-of-the-art transistors in speed, power dissipation, gain, etc. Neither did Ref. 1 make such a claim. In fact, we have reasons to believe that spin field effect transistors may not be competitive with conventional transistors in logic applications, but might have niche applications in memory.[15] They may also have better noise margin since spin does not easily couple to stray electric fields, unlike charge.

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