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Electronic analog of the electro-optic modulator

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We propose an electron wave analog of the electro-optic light modulator. The current modulation in the proposed structure arises from spin precession due to the spin-orbit coupling in narrow-gap semiconductors, while magnetized contacts are used to preferentially inject and detect specific spin orientations. This structure may exhibit significant current modulation despite multiple modes, elevated temperatures, or a large applied bias.

Recent experiments have shown that quantum interference effects play a significant role in electron transport in nanostructures at low temperatures.[1] These effects are analogous to those well known in microwave or optical networks and quantum device concepts based on microwave analogies have been studied.[2,3] A number of microwave and optical devices like the magic tee or the electro-optic light modulator rely on the two allowed polarizations of electromagnetic waves. An obvious question to ask is whether analogous devices are conceivable based on the two possible spin polarizations of electron waves. The purpose of this letter is to explore this possibility theoretically.

The current modulation in the proposed structure arises from spin precession due to the spin-orbit coupling in narrow-gap semiconductors, while magnetized contacts are used to preferentially inject and detect specific spin orientations. The basic effect can be understood by analogy with the electro-optic light modulator shown in Fig. 1(a). A polarizer at the input polarizes the light at 45° to the y axis (in the y-z plane) which can be represented as a linear combination of z- and y-polarized light.

$$\underset{(45^\circ\ \text{pol.})}{\begin{pmatrix}1\\1\end{pmatrix}} = \underset{(z\ \text{pol.})}{\begin{pmatrix}1\\0\end{pmatrix}} + \underset{(y\ \text{pol.})}{\begin{pmatrix}0\\1\end{pmatrix}}. \tag{1}$$

As this light passes through the electro-optic material, the two polarizations suffer different phase shifts k_1L and k_2L because the electro-optic effect makes the dielectric constant ϵ_{zz} slightly different from ϵ_{yy}. The light emerging from the electro-optic material is represented as $\begin{pmatrix}e^{ik_1L}\\e^{ik_2L}\end{pmatrix}$. The analyzer at the output lets the component along $\begin{pmatrix}1\\1\end{pmatrix}$ to pass through. The output power P_0 is given by

$$P_0 \propto \left| (1\ 1)\begin{pmatrix}e^{ik_1L}\\e^{ik_2L}\end{pmatrix}\right|^2 = 4\cos^2\frac{(k_1-k_2)L}{2}. \tag{2}$$

The light output is modulated with a gate voltage that controls the differential phase shift $\Delta\theta = (k_1 - k_2)L$.

The analogous device based on electron waves is shown in Fig. 1(b). The polarizer and analyzer can be implemented using contacts made of a ferromagnetic material like iron.[4] At the Fermi level in such materials the density of states for electrons with one spin greatly exceeds that for the other, so that the contact preferentially injects and detects electrons with a particular spin. Spin current polarization up to ~50% has been experimentally demonstrated utilizing Permalloy contacts.[4,5] Although further work in this area is needed, implementation of the spin polarizer and analyzer seems feasible. A contact magnetized in the x direction preferentially launches and detects electrons spin polarized along positive x which is represented as a linear combination of positive z-polarized and negative z-polarized electrons.

$$\underset{(+x\ \text{pol.})}{\begin{pmatrix}1\\1\end{pmatrix}} = \underset{(+z\ \text{pol.})}{\begin{pmatrix}1\\0\end{pmatrix}} + \underset{(-z\ \text{pol.})}{\begin{pmatrix}0\\1\end{pmatrix}}. \tag{3}$$

Finally we need the analog of an electro-optic material which will introduce a differential phase shift between $+z$ polarized and $-z$ polarized electrons that can be controlled with a gate voltage. Narrow-gap semiconductors like InGaAs provide just what we need, as we will describe below.

It has been established both theoretically[6,7] and experimentally[8,9] that in 2DEGs in narrow-gap semiconductors there is an energy splitting between up-spin and down-spin electrons even when there is no magnetic field. The dominant mechanism for this "zero-field spin splitting" is believed to be the Rashba term in the effective mass Hamiltonian:

$$H_R = \eta(\sigma_z k_x - \sigma_x k_z). \tag{4}$$

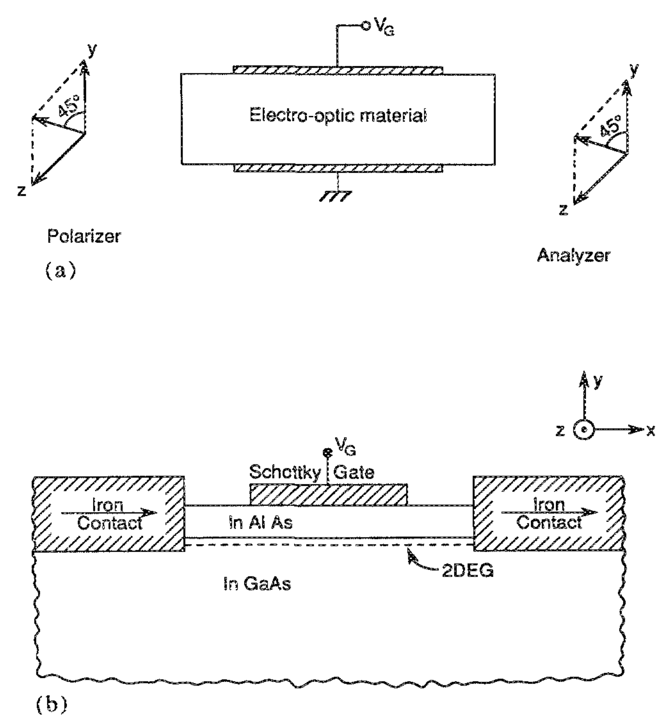

FIG. 1. (a) Electro-optic modulator; (b) proposed electron wave analog of the electro-optic modulator.

This term arises from the perpendicular electric field at heterojunction interfaces. Other mechanisms such as the inversion asymmetry term also contribute to the zero-field spin splitting; however, we will ignore these here as they are usually smaller in narrow-gap semiconductors. It is easy to see that the Rashba term causes $+z$ polarized and $-z$ polarized electrons with the same energy to have different wave vectors k_1 and k_2. Consider an electron traveling in the x direction with $k_z = 0$ and $k_x \neq 0$ (we assume that the electron forms a 2DEG in the x-z plane). The Rashba term H_R is then equal to $\eta\sigma_z k_x$. This raises the energy of z-polarized electrons by ηk_x and lowers that of $-z$ polarized electrons by the same amount. It is as if the electrons feel a magnetic field B_z proportional to k_x ($\eta k_x \rightarrow \mu_B B_z$, μ_B being the Bohr magneton).

$$E(z \text{ pol.}) = \hbar^2 k_{x1}^2/2m^* - \eta k_{x1}, \tag{5a}$$

$$E(-z \text{ pol.}) = \hbar^2 k_{x2}^2/2m^* + \eta k_{x2}. \tag{5b}$$

From Eqs. (5a) and (5b) we obtain

$$k_{x1} - k_{x2} = 2m^*\eta/\hbar^2. \tag{6}$$

It is apparent that a differential phase shift

$$\Delta\theta = (k_{x1} - k_{x2})L = 2m^*\eta L/\hbar^2 \tag{7}$$

is introduced between up- and down-spin (or z polarized and $-z$ polarized) electrons, which is proportional to the spin-orbit coefficient η. An obvious question to ask is whether η is large enough that a phase difference of π can be introduced within a mean free path. For InGaAs/InAlAs heterostructures, from the experimentally observed zero-field spin splitting, η was estimated to be $\sim 3.9 \times 10^{-12}$ eV m.[9,10] This yields $L(\theta = \pi) = 0.67\ \mu$m; mean free paths $\gtrsim 1\ \mu$m are not uncommon in high-mobility semiconductors at low temperatures. The spin-orbit-coupling constant η is proportional to the expectation value of the electric field at the heterostructure interface[6] and, in principle, can be controlled by the application of a gate voltage. However, this has not yet been demonstrated experimentally.

It thus seems feasible, in principle, to implement the electron wave analog of an electro-optic light modulator using iron contacts to implement the polarizer and the analyzer and a narrow-gap semiconductor like InGaAs to introduce a gate-controlled differential phase shift between the two polarizations. So far, however, we have considered only electrons traveling along x. In practice, of course, we have an angular spectrum of electrons in the x-z plane. The above effect is reduced as the direction of propagation of the electron turns away from the x axis. This is because for electrons with nonzero k_x and k_z the eigenstates are obtained by diagonalizing the full Hamiltonian:

$$H = H_0 + H_R = \begin{pmatrix} \dfrac{\hbar^2(k_x^2 + k_z^2)}{2m^*} + \eta k_x & -\eta k_z \\ -\eta k_z & \dfrac{\hbar^2(k_x^2 + k_z^2)}{2m^*} - \eta k_x \end{pmatrix}. \tag{8}$$

With $k_z = 0$, the eigenstates are $\binom{1}{0}$ and $\binom{0}{1}$ so that the incoming electron beam $\binom{1}{1}$ splits equally between them as shown in Eq. (3). But if $k_x = 0$, the eigenstates are $\binom{1}{1}$ and $\binom{1}{-1}$ so that the incoming beam is not split at all. It goes entirely into one of the eigenstates. Consequently no current modulation is expected. As the angle θ of propagation of the electrons with the x axis is increased, it can be shown that the effect is reduced gradually to zero at $\theta = 90°$.

For larger overall current modulation it seems advisable to restrict the angular spectrum of the electrons. This can be done with a confining potential $V(z)$ that confines the electrons in a waveguide.

$$H = \begin{bmatrix} -\dfrac{\hbar^2}{2m^*}\left(\dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial z^2}\right) + V(z) - i\eta\dfrac{\partial}{\partial x} & i\eta\dfrac{\partial}{\partial z} \\ -i\eta\dfrac{\partial}{\partial z} & -\dfrac{\hbar^2}{2m^*}\left(\dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial z^2}\right) + V(z) + i\eta\dfrac{\partial}{\partial x} \end{bmatrix} \tag{9}$$

To find the eigenstates of H we use the unperturbed ($\eta = 0$) eigenstates as a basis set. These eigenstates can be labeled with three indices: the subband index m, the wave vector k in the x direction, and the spin.

$$H_0|m,k\rangle = E_{m,k}|m,k\rangle \tag{10a}$$

$$E_{m,k} = \epsilon_m + \hbar^2 k^2/2m^*. \tag{10b}$$

The two spins $\binom{1}{0}$ and $\binom{0}{1}$ are degenerate. The subband energy ϵ_m is obtained by solving the eigenvalue equation

$$\left(-\frac{\hbar^2}{2m^*}\frac{d^2}{dz^2} + V(z)\right)\phi_m(z) = \epsilon_m\phi_m(z). \tag{11}$$

The Rashba term H_R leads to matrix elements coupling the eigenstates of H_0 as follows ($+$ and $-$ stand for $\binom{1}{0}$ and $\binom{0}{1}$, respectively):

$$\langle m',k',+|H_R|m,k,+\rangle = +\eta k\delta_{m',m}\delta_{k',k}, \tag{12a}$$

$$\langle m',k',-|H_R|m,k,-\rangle = -\eta k\delta_{m',m}\delta_{k',k}, \tag{12b}$$

$$\langle m',k',+|H_R|m,k,-\rangle = \frac{\eta}{\hbar}\langle m'|p_z|m\rangle\delta_{k',k}. \tag{13}$$

The eigenstates of H will clearly involve linear combinations of different subbands due to the matrix elements in Eq. (13). However, if the different subbands are sufficiently far apart in energy, then we can neglect this subband mixing. We have estimated the maximum width w of the confining potential well for which the intersubband mixing can be neglected. For both rectangular and parabolic potential wells, we find that w should be $\ll \hbar^2/\eta m^*$. With $\eta = 3.9 \times 10^{-12}$ eV m and $m^* = 0.046m_0$, this yields $w \ll 0.43\ \mu$m, which is within the reach of present day technology. Provided the intersubband mixing can be neglected, the main effect of the Rashba term H_R is to split the degeneracy between the two spins through the matrix elements in Eqs. (12a) and (12b).

$$E_{m,k,s} \simeq \epsilon_m + \hbar^2 k^2/2m^* + \eta k s. \quad (14)$$

Here $s = -1$ denotes $\binom{0}{1}$ and $s = +1$ denotes $\binom{1}{0}$. The wave vectors k_1 and k_2 corresponding to the same energy E for the two spins differ by

$$k_1 - k_2 = 2m^*\eta/\hbar^2, \quad (15)$$

just as we discussed earlier [Eq. (6)] for plane unguided waves.

It is interesting to note that the differential phase shift $\Delta\theta = 2m^*\eta L/\hbar^2$ is independent of m,k; it is the same for all subbands and for all energies. This is an important advantage for device applications. Usually quantum interference devices have to be single moded in order to obtain large effects, because the differential phase shift between the interfering paths varies from one mode to another and interference effects tend to wash out when multiple modes are involved. For the same reason, it is important to use low temperatures and low voltages so that there is very little spread in the energies of the electrons involved in the conduction process. But in the device discussed above, the differential phase shift between the two spin components is the same ($= 2m^*\eta L/\hbar^2$) for all energies and mode numbers and can be controlled through the spin-orbit coupling coefficient η. Consequently it may be possible to achieve large percentage modulation of the current even in multimoded devices operated at elevated temperatures and larger applied bias. From an experimental point of view there appears to be at this time two main unknowns: (1) how well the spin polarizer and analyzer can be implemented in a 2DEG with magnetized contacts and (2) to what extent η can be controlled with a gate voltage.

Current modulation in the structure described here arises from spin precession due to the spin-orbit coupling in narrow-gap semiconductors. More sophisticated structures (such as an Aharonov–Bohm ring[11] with different spin-orbit coupling coefficients in the two arms) are conceivable where current modulation could arise from spin interference as in weak antilocalization experiments.[12] Such structures may not require a polarizer or an analyzer.

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