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High efficiency nonvolatile ferromagnet/superconductor switch

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A composite magnetosuperconducting switch is proposed. The device, which is based on Andreev reflection at the superconductor/ferromagnet contact, combines high efficiency with nonvolatility. The *low*-impedance state of the device corresponds to the *normal* state of the superconductor, whereas the *high*-impedance state corresponds to the *superconducting* state. The proposed device does not require high-quality Andreev contacts; on the contrary, interface scattering significantly increases the efficiency of the device. Up to 1000%–2500% efficiency can be achieved with the existing ferromagnetic materials. The device can be used as a basic element for nonvolatile logic and memory. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1481987]

New concepts and devices based on the electron spin rather than the charge play an increasingly prominent role in electronics (*spintronics*).[1,2] Advanced by the discovery of the giant magnetoresistance (GMR) effect,[3] many unique features of spin transport have been exploited to produce new, robust effects, not feasible within conventional electronics. Spin polarization in semiconductors has been successfully coupled with circularly polarized light pulses,[4] spin injection into a semiconductor[5] has enabled spin-emitting diodes,[6] and ferromagnetic semiconductors *p*-*n* junctions[7] have been realized.[8]

Traditional GMR and tunneling magnetoresistance (TMR)[9] devices have been used in magnetic sensors[10] as well as in nonvolatile memory.[11] Nonvolatile reprogrammable logic[12] may eventually achieve true on/off operation, but only if materials with very high (close to 100%) spin polarization P will become available. However, even with the improved efficiency, performance of the devices built solely with magnetic elements, especially in the submicron regime, is strongly affected by their shape and size. The optimization of switching dynamics and complex micromagnetic phenomena due to domain structure, magnetic singularities,[13] and coupling between magnetic layers, will be required to implement working devices.

Extensive work has also been done to build low-power superconducting electronic devices, including memory and logic. Josephson junctions are widely used in superconducting quantum interference device (SQUID) magnetometers as well as in the Rapid Single Flux Quantum (RSFQ) logic.[14] RSFQ combines remarkable data processing speed (up to ~1 THz) with intrinsic memory based on the absence (0) or presence (1) of a single-flux quantum in a SQUID loop. On the other hand, the RSFQ memory density is limited by the size of the SQUID loop, and noninterrupted refrigeration is required to maintain its logic state. Many other interesting superconducting devices have been proposed. They are generally based on locally suppressing the superconductivity, either by applying the gate voltage (field-effect transistors),[15,16] fringe magnetic field[17] (controllable weak links)[18] or by nonequilibrium quasiparticle injection.[19]

In this letter, we explore theoretically an original device involving both superconductivity *and* magnetism. This device, based on the so-called *Andreev reflection*, provides an alternative element for high-density nonvolatile memory and logic, unaffected by room-temperature cycling.

In the Andreev process,[20] which takes place at the interface between a normal metal and a superconductor, an electron in the normal metal is reflected back as a hole, while a Cooper pair propagates inside the superconductor. The hole reflected into the normal metal occupies the band with the spin opposite to that of the incoming electron. This spin *selectivity* is unimportant when there is no spin asymmetry in the system, as in the case of conventional, nonmagnetic metals. However, as de Jong and Beenakker realized in 1995,[21] Andreev reflection in ferromagnets and in nonmagnetic metals has completely different properties. Specifically, the conductance below the superconducting gap, which is twice the normal conductance in conventional metals,[22] is suppressed in ferromagnets, due to the fact that the number of conductivity channels for the minority spin states is different from the one for the majority spin states. This suppression is especially pronounced in the so-called *half metals* that have only one type of the spin-polarized carriers (majority) at the Fermi level at low temperatures. It was first observed experimentally by the NRL group using the point contact technique[23] and the Cornell group,[24] which used the nanocontact geometry. Almost complete suppression of the subgap conductance was observed in CrO_2,[23,25] which is believed to be half metallic,[26] and in disordered $La_{0.7}Sr_{0.3}MnO_3$, which we believe to be a *transport* half metal.[27]

The proposed device, which we call a nonvolatile Andreev switch (NOVAS) consists of an Andreev nanocontact between a highly spin-polarized magnetic metal and a superconductor, which can be switched from superconducting to normal state by the edge field of a ferromagnetic control film positioned on top of the contact, using the technique introduced in Ref. 28. The edge field of the control film can be

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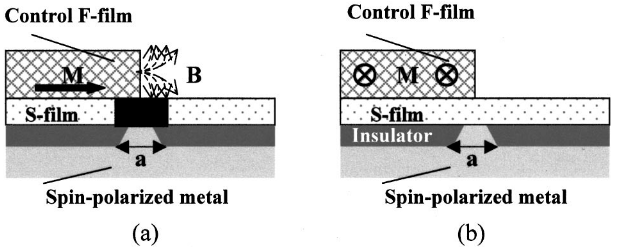

FIG. 1. (a) and (b) Schematic of NOVAS. The device consists of an Andreev nanocontact between a highly spin-polarized ferromagnetic film (bottom electrode) and a superconducting film (top electrode). A soft ferromagnetic control film (F), e.g., permalloy, is fabricated on top of the superconductor. The resistance of the device is modulated by the F film, whose fringe field (approximately several kOe) suppresses superconductivity when its magnetic moment is in plane (a). The normal area (shown by a black rectangle) is spanned over a distance comparable with the thickness of the F film, typically about 100 nm, which is generally much larger than the contact size, a ~3–30 nm. Configuration (a) corresponds to the *low-impedance* state of the device, while no fringe field in the contact (b) corresponds to the *high-impedance* state of the device.

modulated from ~0 to several kOe by rotating the magnetic moment $\boldsymbol{M}$ in the $x-y$ plane of the film by 90° (see Fig. 1). While these edge fields are large enough to quench the superconductivity in Sn or Pb, for example,[17] the magnetization rotation can be done by using a much smaller in-plane field if the ferromagnetic control film is fabricated of a soft magnetic material (e.g., permalloy).[29] The suppression of Andreev reflection in a ferromagnet/superconductor (FS) contact leads to *high impedance* when the superconductor is in the superconducting state and to *low impedance* when the superconductor is in the normal state. Nominally, for a half metal, the efficiency $R_{\text{high}}/R_{\text{low}}$ of such a device is infinite at $T=0$ (the conductance at zero bias is zero). In reality, this ratio will be limited by spin flips, spin–orbit interaction, and other secondary processes. Of course, GMR/TMR type devices would have also had a nominally infinite efficiency if half-metallic junctions could be fabricated in practice. Unfortunately, the efficiency of conventional magnetic devices decline rapidly when P is reduced from 100%; on the other hand, a NOVAS will retain its high efficiency even for materials with $P\sim 70\%-80\%$, which are readily available. As we will show next, the NOVAS efficiency can be further *increased* by using *low-quality* (high scattering) contacts, provided that there is no spin–flip scattering.

Interface scattering at the normal/superconducting interface can be described analytically in the two opposite limits. In the ballistic or Sharvin[30] limit (the electron mean free path ℓ is larger than the contact size a) the interface scattering is usually well described by the standard BTK model,[31] assuming specular interface scattering with a repulsive one-dimensional potential at the interface, $U=Z\delta(x)/\hbar v_F$, where v_F is the Fermi velocity.[22] Using a generalized BTK approach,[21] one can also describe the case of an arbitrary P, which can be considered as a linear combination of nonpolarized and half-metallic cases.[32] For a ferromagnet at $T=0$, the conductance G_{FM}/G_0 (Ref. 33) is:

$$\frac{G_{FM}}{G_0}=\left\{\begin{array}{ll}\dfrac{(1-P)2(1+\beta^2)}{\beta^2+(1+2Z^2)^2} & V<\Delta \\ \dfrac{(1-P)(2\beta)}{1+\beta+2Z^2}+\dfrac{P(4\beta)}{(1+\beta)^2+4Z^2}, & V>\Delta\end{array}\right\},$$

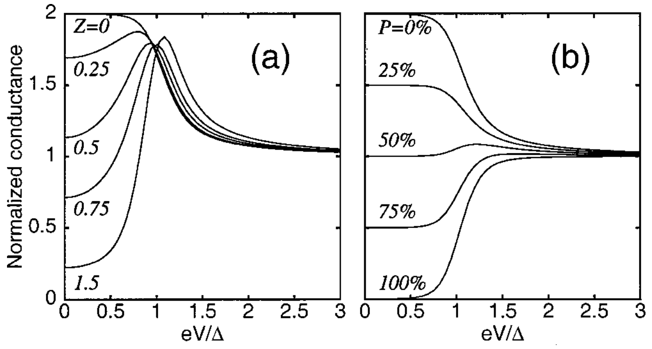

FIG. 2. (a). Normalized conductance curves for an unpolarized metal for different barrier transparencies determined by a dimensionless parameter Z, varying from $Z=0$ (clean interface, top curve) to $Z=1.5$ (low-transparency barrier, bottom curve). (b) Normalized conductance for different values of the spin polarization and clean interface ($Z=0$).

$$\text{where}\quad \beta=\frac{V}{\sqrt{V^2-\Delta^2}}. \tag{1}$$

In the diffusive or Maxwell limit ($\ell<a$), the electron quasimomentum is no longer a good quantum number. Fortunately, the Landauer–Büttiker formalism used earlier by Beenakker for the Andreev process in the nonmagnetic diffusive case[34] is applicable to the diffusive spin-polarized case as well.[32] In Ref. 32, the diffusive contact was treated as a disordered normal region of length L adjacent to a ballistic Andreev contact.[35] If $\ell<L<N_{cc}\ell$, where N_{cc} is the number of conductance channels, the problem can be solved analytically and the answer at $T=0$ is[36]:

$$\frac{G_{FM}}{G_0}=\left\{\begin{array}{ll}(1-P)\dfrac{1+\beta^2}{2\beta}\operatorname{Im}[F(-i\beta)-F(i\beta)], & V<\Delta \\ (1-P)\beta F(\beta)+P\beta F\left[\dfrac{(1+\beta)^2}{2}-1\right], & V>\Delta\end{array}\right\},$$

$$F(x)=\frac{\cosh^{-1}(2Z^2+x)}{\sqrt{(2Z^2+x)^2-1}}. \tag{2}$$

G_{FM}/G_0 at an experimentally relevant temperature $T=0.1\Delta$ for different values of P for a ballistic (Sharvin) contact is plotted in Figs. 2(a) and 2(b) as a function of voltage, using the theory outlined herein. One can see that even in a nonmagnetic material, the conductance is suppressed by the interface scattering faster in the superconducting state, than in the normal $R_{\text{sc}}/R_{\text{norm}}=(1+2Z^2)^2/2(1+Z^2)$. However, the dynamic range for a nonmagnetic contact is rather limited, because large Z values ($Z\gg 1$, "tunnel junction regime") correspond to small currents and thus are not suitable for most electronics applications, whereas an acceptable $Z\approx 1$ yields small ratios $R_{\text{sc}}/R_{\text{norm}}\approx 2$ [Fig. 2(a)]. On the other hand, for an *ideal* interface, the $R_{\text{sc}}/R_{\text{norm}}$ for an FS junction is not too high either (unless $P\approx 100\%$) [Fig. 2(b)].

The suggested NOVAS combines reasonably high P *and* high interface scattering, yielding a dramatic enhancement of the $R_{\text{sc}}/R_{\text{norm}}$ ratio without significantly reducing the current. For instance, in the ballistic regime a material with a modest $P=75\%$ and $Z=1$ gives $R_{\text{sc}}/R_{\text{norm}}\approx 9$ (Fig. 3). A diffusive contact is even more efficient. As an upper curve of the Fig. 3 demonstrates, a diffusive contact with the same parameters

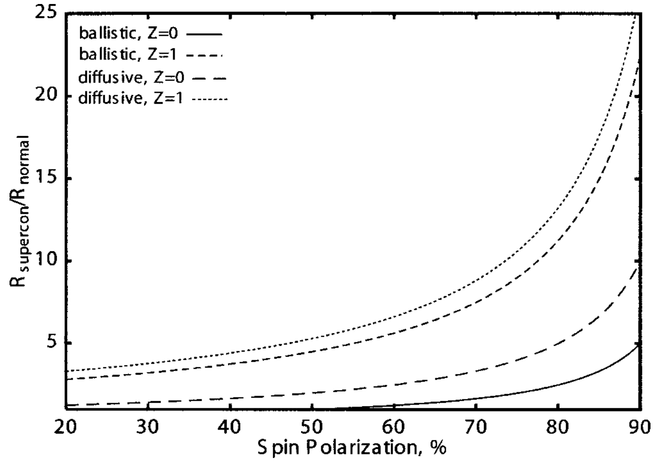

FIG. 3. Impedance ratios of superconducting-to-normal states of NOVAS as a function of spin polarization P for $Z=0$ (two bottom curves) and $Z=1$ (two top curves) for the ballistic and diffusive cases. For a reduced barrier transparency $(Z=1)$, the ratio in both cases significantly increases.

has the efficiency $R_{\mathrm{sc}}/R_{\mathrm{norm}} \approx 11$, and for $P=90\%$ the efficiency $R_{\mathrm{sc}}/R_{\mathrm{norm}} > 25$! It is instructive to compare a NOVAS to a GMR/TMR type device, where two ferromagnetic films are switched between the high and low resistance states. Their $R_{\mathrm{high}}/R_{\mathrm{low}}$ ratio can be roughly estimated from the Julliere model,[37] $R_{\mathrm{high}}/R_{\mathrm{low}} \approx (1+P^2)/(1-P^2)$, and for the same $P \approx 75\%$ is only about 3.5.

In summary, we propose an original magnetosuperconducting device based on Andreev reflection in ferromagnets. The memory state of the device is determined by the direction of magnetic moment $\boldsymbol{M}$ in the control ferromagnetic element. Thus, the switching rate of the device is limited by magnetization reversal time of a single-ferromagnetic film,[38] which can be of the order of picoseconds $(f \sim 1\ \mathrm{GHz})$, as has recently been reported in Co films.[39] Importantly, the presence of an oxide layer or any other nonuniformity (including Fermi velocity mismatch) between a spin-polarized material and a superconductor only improves the device performance. Our calculations demonstrate that the device will have outstanding on/off ratios both in the ballistic and diffusive regimes, with the interface scattering enhancing these ratios up to about 1000% at $P=75\%$ and up to 2500% for $P=90\%$ and $Z \sim 1$ in both cases. At the same time, a NOVAS is truly nonvolatile in a sense, that it preserves its state at room temperature for a typical high-Curie-temperature ferromagnetic control film (e.g., permalloy). With unconventional superconductors, it may be possible to increase the operational temperature of the device to about 10–15 K. Another intriguing possibility is to control Andreev reflection by electric fields via a PZT film coupled to a field-effect superconductor,[40] which may eventually allow device operation at 77 K.

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