Superconducting electron focusing and guiding based on the Andreev reflection mechanism

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Based on the principle of Andreev reflection, we suggest a novel normal-metal-superconductor composite structure capable of electron focusing and guiding. Such a structure may be used as a switching device. The resolution and performance of a model system have been evaluated numerically.

Composite superconducting systems generally refer to those in which the superconducting gap $\Delta(r)$ is a spatially varying function, as near a normal-metal-superconductor (NS) interface. The conventional NS systems possess many unique properties, most of which have been successfully explained by means of Bogoliubov–de Gennes equations governing the excitations in spatially inhomogeneous superconductors.[1] One of the most interesting effects is the Andreev, or electron-hole, reflection[2] (AR), a quasiparticle scattering process on an NS interface. If an electron with energy E less than $\Delta(r)$ is incident onto the interface from the N side with a group velocity $\mathbf{v}_g$, it can propagate into the S side only if it pairs with another electron, since the gap in the pair spectrum is zero. To conserve energy and momentum a reflected hole with a reversed group velocity $-\mathbf{v}_g$ and a negative effective mass is formed and travels back along the original electron path. AR is fundamentally different from the ordinary specular reflection, where the electron is reflected only with the normal component of its velocity reversed after reflection. AR has been observed in point contact and two-point-contact experiments.[3–5]

In a typical measurement, a point contact (a fine wire with one end etched to a diameter about 1 μm) is attached to a normal-metal surface. A current is sent through the contact, injecting electrons like a point source. At the NS interface, holes are generated and Andreev-reflected back to the *same* point contact, from which an enhanced current can be detected. As the bias voltage increases above the gap potential, this enhancement vanishes since single electrons can enter into the superconductor directly. Unlike the specularly reflected electrons that are divergent, the reflected holes are always focused towards the original point contact. If two separated contacts are used, one as an injector and the other as a detector, it is possible to focus the electrons to the detector by an appropriate magnetic field parallel to the interface. This property special to AR has been demonstrated by Bozhko *et al.*[4] and Benistant *et al.*[3]

As semiconductor structures continue to be miniaturized and electron mobility increases, the subject of electron optics which deals with the wave mechanics of the electrons has received a great deal of interest. New semiconductor mesoscopic structures based on electron optics have been fabricated and studied, promising faster and more efficient solid-state devices. We feel that the fascinating AR mechanism offers a new natural focusing capability without the use of electromagnetic lenses for solid-state electron optics.

Taking advantage of the AR mechanism, we have designed a mesoscopic structure shown in Fig. 1 which is capable of electron focusing and guiding. The thin-film-based structure, with an NS *edge* interface instead of a commonly used planar interface, consists of an injector and a periodic array of detectors. These injector and detectors are integral parts of the normal-metal film and can be patterned with electron lithographic techniques. NS edge interfaces have been successfully fabricated by some groups[6] used for various superconducting devices. The operation of the device shown in Fig. 1 is described as follows. During the measurement, electrons are injected via a bias voltage near the NS interface. All the Andreev-reflected holes are naturally focused back to the injector. However, with an external magnetic field perpendicular to the thin film as shown in Fig. 1, the reflected holes will be focused to a new location x. If x is in the vicinity of a detector, there will be a current picked up by this detector, while the currents in other detectors will be very small. Every detector has its own focusing field. In effect, such a device functions as a magnetically controlled microswitch. The on-off action in each channel is accurately controlled by the magnetic field.

In a conventional setup[3,5] to study AR, an NS planar interface is first fabricated and very fine wires are attached to the N surface as point contacts. The electron beam from a point contact is divergent in all directions (solid angle 2π). Only those electrons and holes in the plane perpendicular to the magnetic field can be focused to another location (with some dispersion). Thus, the reflected current picked up by another point contact is so minute that only a highly sensitive instrument can detect the signal. In our structure, because the injector and the detectors are integral parts of the N film, the electrons are confined within the thin film and all contribute to the detector current. This feature will significantly enhance the detector current.

To calculate the detector current and the focusing ability, we set up a coordinate system in Fig. 2, where all the geometrical parameters are labeled. A simple ballistic calculation provides the relation between the final position x and various parameters such as the initial electron angle θ_0,

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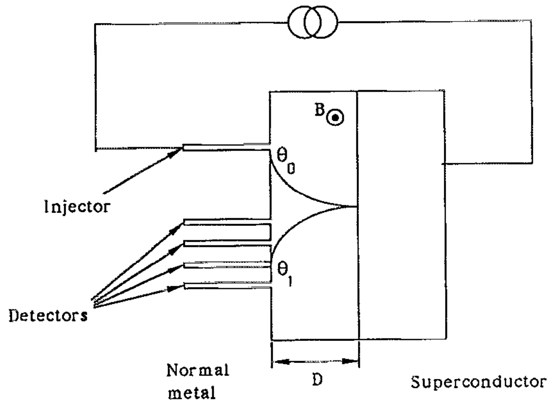

FIG. 1. Schematic of a proposed magnetic switching device based on the Andreev reflection mechanism. The normal-metal-superconductor interface is an edge interface between the N and S thin films. The current injector and detectors are integral parts of the N film patterned with lithography. External magnetic field is perpendicular to the thin-film structure.

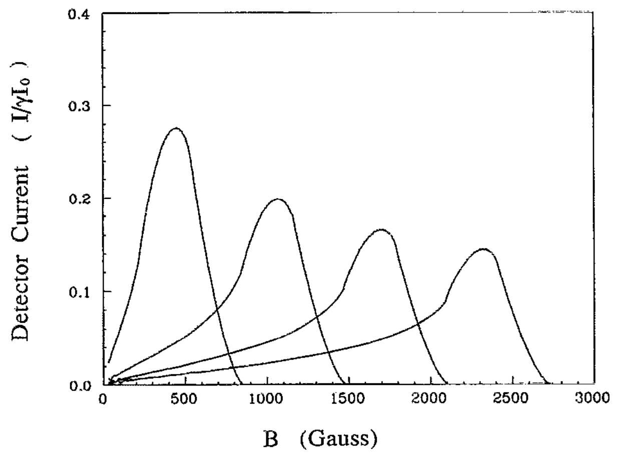

FIG. 3. Detector currents in four channels in units of γI_0 (γ: AR reflectivity) as functions of an external magnetic field for the structure shown in Figs. 1 and 2 with parameters $t_0=1000$ Å, $D=5$ μm, $k_F(\text{Ag}) = 1.19\times 10^8$ cm^{-1}. The focusing magnetic fields are those where detector currents reach maximum.

magnetic field, and geometrical dimensions (see Figs. 1 and 2):

$$x=\frac{D}{\alpha}\,[2\sqrt{\sin^2\theta_0+2\alpha\cos\theta_0-\alpha^2}-\sin\theta_0+\sin\theta_1], \qquad (1)$$

$$\sin\theta_1=-\sqrt{\sin^2\theta_0+4\alpha\cos\theta_0-4\alpha^2}, \qquad (2)$$

where $\alpha=eBD/\hbar k_F$, k_F is the Fermi wave vector of the metal which we will choose silver, and D is the width of the N film (see Fig. 2). The focusing position is obtained by requiring $\partial x/\partial\theta_0=0$,

$$\text{Focusing position:}\quad x_f=\frac{2D}{\alpha}\,(1-\sqrt{1-\alpha^2}). \qquad (3)$$

Therefore, the focusing position x_f depends on magnetic field B. For different B, holes are focused at different locations.

Since the width of the injector is comparable to that of detectors and to the separation between detectors, the injector cannot be treated as a point source in calculating the detector current. Instead, it is a superposition of point sources. Suppose the injector current is $I_0=eN_0$ with N_0 being the number of passing electrons per unit time, then the number of electrons passing through a small region $x_0-(x_0+dx_0)$ in the injector is $dn_0=(dx_0/t_0)N_0$ with t_0 being the width of the injector. We assume that electrons flow uniformly across the injector and that every point source dx_0 injects electrons with uniform angular distribution ($0\leqslant\theta_0\leqslant\pi$). The current picked up by any detector is then given by

$$I=\frac{\gamma I_0}{\pi t_0}\int_{-t_0/2}^{t_0/2}dx_0\int_{\theta_0(x_a)}^{\theta_0(x_b)}d\theta_0(-\sin\theta_1), \qquad (4)$$

where γ is AR probability (or reflectivity) at the NS interface; $\theta_0(x_a)$ and $\theta_0(x_b)$ are the initial angles of those injecting electrons that reach the two edges (x_a, x_b) of a detector—they are obtained by solving Eqs. (1) and (2) with x substituted by x_a-x_0 and x_b-x_0, respectively.

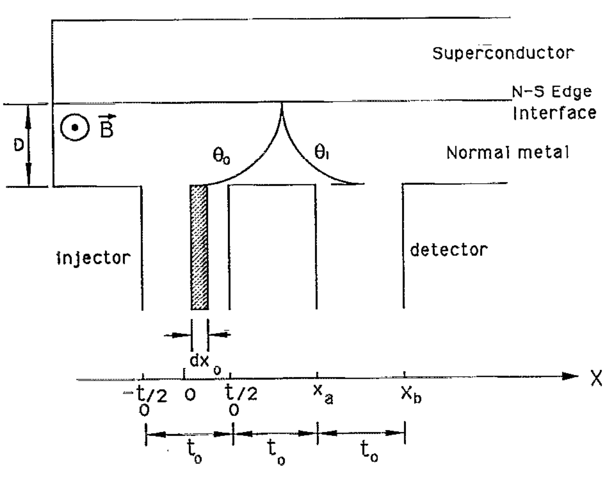

FIG. 2. A coordinate system used to calculate the detector current of the structure shown in Fig. 1 (see text).

We have carried out a numerical calculation for the structure shown in Figs. 1 and 2. The geometrical parameters used are as follows: the width of the injector and detectors $=1000$ Å, the separations between the injector and the first detector as well as between the detectors $=1000$ Å, the width (D) of the N film $=5$ μm. Our choice of the normal metal is silver (Ag) for its long electron mean free path [as high as 700 μm for single-crystal Ag (Ref. 5) at 4.2 K]. The Fermi wave vector for Ag is $k_F=1.19\times10^8$ cm^{-1}. Figure 3 shows the currents received in each detector channel in units of γI_0. Every detector current has a maximum at a unique magnetic field which we call the focusing field. As can be seen, every current peak is well resolved, indicating a rather satisfactory focusing capability in the proposed device. In Fig. 4, we plot the currents received in each channel for different focusing fields $H_i=$ 452, 1063, 1701, and 2318 G, respectively). At H_1, the current I_1 in the first channel is maxi-

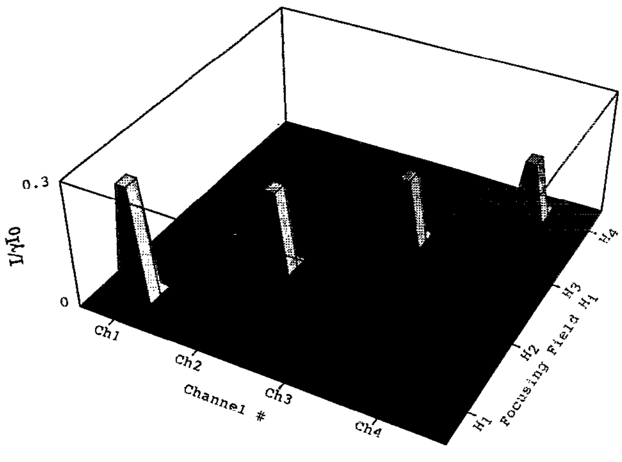

FIG. 4. Currents ($I/\gamma I_0$) received at each detector (channel Nos. 1–4) at different focusing fields (H_1–H_4) with the same parameters used in Fig. 3.

mum and the currents I_i in other channels are very small (not exactly zero, due to an intrinsic dispersion). When H is increased to H_2, I_2 becomes a maximum, and so on. In general, if holes are focused at channel n, there will be no current in the preceding $n-1$ channels, only a tiny current in the $n+1$ channels. Therefore, to direct current to a particular channel, one can simply apply its corresponding focusing magnetic field. The detector current is proportional to the AR probability γ. For a good NS interface, $\gamma \simeq 1$ as demonstrated in some measurements.[5] In this case the receiving current is about 25% of the injecting current. For a conservative estimate, if γ is reduced to 0.5, the receiving current is about 10% of the injecting current, which can be easily measured. The specularly reflected electrons are divergent, and contribute very little to the signal due to the small size of the detectors. The focusing field for each detector can be adjusted by using different sets of geometrical parameters.

In the above calculation, surface scattering which tends to remove carriers from the "beam" was not considered. This is because under equilibrium, surface static charges, and the induced electrostatic field tend to confine the charges in the thin-film plane. In addition, the injector is a natural part of the normal-metal film, and the scattering at the contact is substantially reduced compared with a conventional point contact. Even if the injected charges were at all angles, there would still be $\sim t/D$ fraction of charges traversing the film without surface scattering. Assuming typical $t \sim 2.5\ \mu$m, $D \sim 5\ \mu$m, this fraction is about 50%, which would not affect the calculated detector current significantly (within 50%).

The fabrication of the device requires a continuous normal-metal film coverage over the vertical step of the superconducting film. This may cause a crack at the junction because the flux of atoms arriving at the substrate has an angular distribution. A plateau on the surface may shadow the lower area and prevents the films in this area from growing at the same rate as the plateau. This problem has been studied extensively in semiconductor device fabrication. The effective methods to obtain good vertical junctions are (1) to increase the source-to-substrate distance, (2) to use an elevated substrate temperature, and (3) to apply a substrate negative bias in a sputtering process. Detailed information about step coverage can be found in Ref. 8.

Even though the AR mechanism has been proposed and confirmed many years ago, technical usage of this phenomenon has not materialized. Our numerical simulation indicates that novel devices based on the AR mechanism are feasible as magnetic multiple-channel switches or solid-state electron waveguides. We believe other applications of AR can also be conceived. The fabrication of our proposed structure, technically demanding notwithstanding, should be achieved by using conventional thin film deposition and electron lithography techniques.

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