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Experiments on Functional Superconducting Electron-Wave Device

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INTRODUCTION A novel superconducting electron-wave device, employing a superconductor(S)/ semiconductor(Sm) structure to handle electron-waves in the Sm, is proposed and its device operation is confirmed experimentally. The S/Sm structure acts like both a mirror and a converging lens for the electron-waves because peculiar quantum process, called Andreev reflection (AR)[1], occurs at the S-Sm boundary. The device consists of an interferometer having the mirror analogous to the Michelson interferometer in optics, and device characteristics is controlled by a gate voltage to change the path length difference between electron-waves in the Sm. The device has a new function of focussing and integrating electron-waves. Therefore, this device will make it possible to achieve such a functional signal processing as Fourier transform. Moreover, this device is suitable for miniaturization, compared with conventional semiconductor electron-wave devices[2,3], since the device properties are insensitive to the roughness of the boundary.

In this late news, operation principle of the functional superconducting electron-wave device and the device characteristics are discussed.

EXPERIMENTS The device consists of a Nb injector with a width of 0.08 μm, a Nb superconducting electrode, and a poly-Si gate electrode 0.2 μm in length, on an As-doped Si wafer (Fig.1(a)). The electron-waves (i.e., electron-like quasiparticle-waves) injected into the Si from the injector are reflected by the Andreev process at the Nb electrode -Si boundary. The reflected electron-waves (i.e., hole-like quasiparticle-waves) are focused on the injector through exactly the same path that the injected electron-waves came from[1]. The injector is also used to detect the electron-waves in the Si. The edge on the Nb electrode has a step 0.2 μm in height that leads to the path length difference between the electron-waves going through path 1 and path 2 in the Si. Since the gate electrode is on the path 1, the effective boundary of the path 1 region, corresponding to the movable mirror, is shifted by applying a gate voltage. As a result, the path 1 length is changed and then the path length difference between the electron-waves is controlled. An SEM photograph of the device, obtained using EB lithography, is shown in Fig.1(b).

RESULTS and DISCUSSION Figure 2(a) shows the dependence of differential resistance between the injector and the Nb electrode on excitation energy for the injected electron-waves, E_e, by changing gate voltage, V_G. The value of E_e corresponds to the injector voltage, V_I. Below E_e of 1.0 meV, the values of resistance decrease from the normal-state resistance observed at E_e =5.0 meV. The decrease arises from the excess current due to the AR. The resistance changes with increasing E_e, and two peaks are observed. One is a broad peak (1st peak) observed at 0.62 meV. The other is a sharp peak (2nd peak) observed at 2.20 meV. The position of the peak energy is changed by increasing V_G (Fig. 2(b)). The position of the 1st peak shifts to a higher energy from 0.62 to 0.73 meV and that of the 2nd peak shifts to a lower energy from 2.20 to 1.95 meV with increasing V_G from 0 to 350 mV. The change in the two peak energies is not monotonous.

To identify the origin of the peak shifts, the change in the resistance is studied numerically. The effective boundary position of the path 1 region is moved, because spatial distribution in the pair potential is changed with increasing carrier concentration in the Si, n, due to the superconducting proximity effect[4], as shown in Fig.3(a). The coherence length in S, ξ_s, for Nb film is about 40 nm, and that in Sm, ξ_{sm}, is increased by n through an increase in V_G. The pair potential values in Nb, Δ_{Nb}, and Si, Δ_{Si}, at the boundary also depend on n[5]. The distance between the injector and effective S-Sm boundary is decreased by increasing n when E_e is smaller than Δ_{Si}. On the contrary, the distance is increased with an increase in n when E_e is larger than Δ_{Nb}. The calculated dependence of the resistance on E_e is shown in Fig. 3(b) for three values of n in the Si. Our calculation assumes plane electron-waves, no inelastic scattering of carriers in the Si, and dependence of electron wavelength on E_e. The resistance changes with an increase in E_e, and shows two peaks below E_e of 3.0 meV. The change in the resistance is caused by interference between the electron-waves. For $n = 5\times10^{25}\ \mathrm{m}^{-3}$, the calculated position of the 1st peak is 0.58 meV, and that of the 2nd peak is 2.1 meV. These two energies agree with the measured results of 0.62 and 2.20 meV for V_G = 0 mV. The calculated 1st peak shifts to a higher energy and the 2nd one shifts to a lower energy with increasing n . The tendency of the peak shifts also agrees with the measured results. Therefore, the origin of the measured change in the resistance is identified as the interference of electron-waves, and the peak shifts come from the change in the phase difference between electron-waves in the Si. We believe this confirms phase-controlled operation of a superconducting device.

CONCLUSION The operation principle of a superconducting electron-wave device, employing the Nb/Si structure as a movable mirror, was confirmed experimentally. The path length difference between electron-waves was controlled by gate voltage. It is expected that this device has high speed and low power consumption similar to Josephson junction devices. Important feature of the device, comes from using the Andreev reflection, is the functional signal processing; sum of the weighted input signals that is based on Fourier transform and threshold logic. This processing can not be achieved by using conventional devices.

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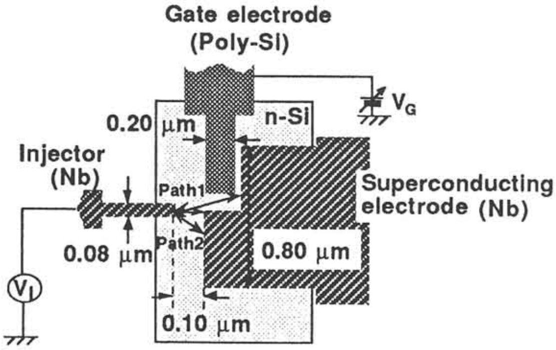
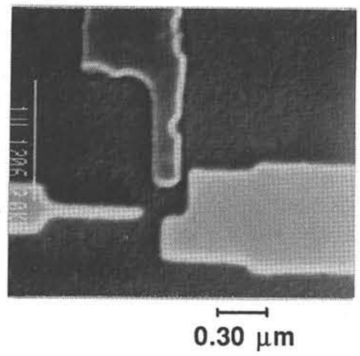
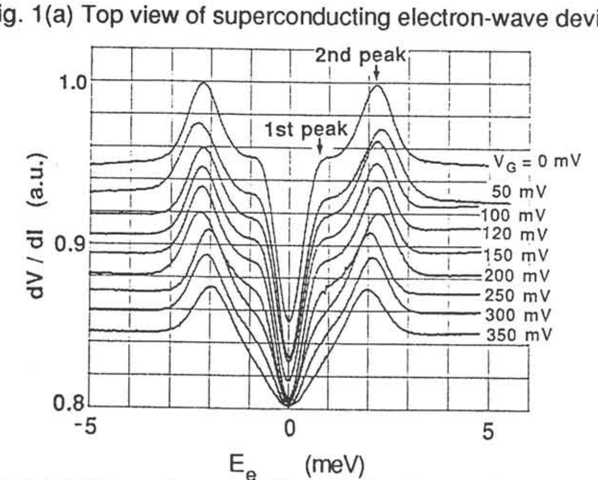


Fig. 1(a) Top view of superconducting electron-wave device.



(b) SEM photograph of device.



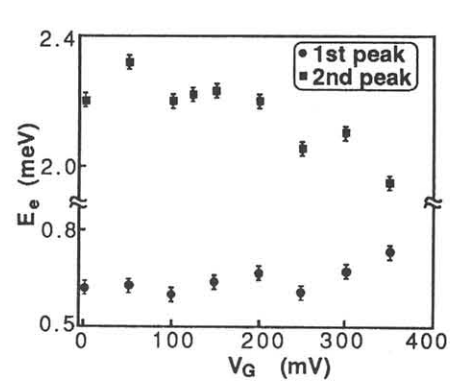
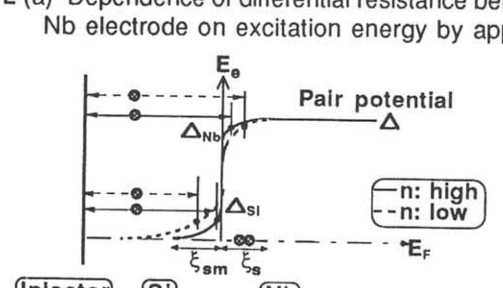


Fig. 2 (a) Dependence of differential resistance between injector and Nb electrode on excitation energy by applying gate voltage.

(b) Position of peak energies as a function of gate voltage.



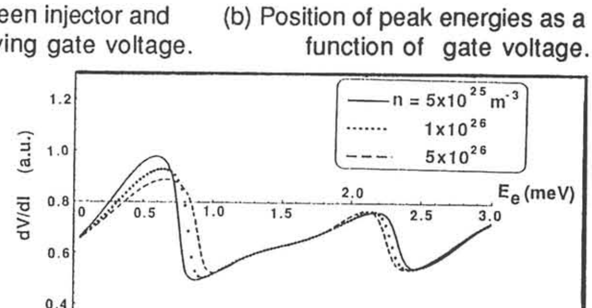


Fig.3 (a) Schematic view of spatial change in pair potential near boundary.

(b) Dependence of calculated resistance on excitation energy by changing carrier concentrations in Si.