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Design and Evaluation of a Magnetically Coupled Aharonov-Bohm Quantum Interference Device

Masafumi YAMAMOTO and Kohji HOHKAWA

NTT LSI Laboratories
3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-01, Japan

A magnetically coupled Aharonov-Bohm quantum interference device capable of 100% relative conductance modulation is designed and its performance is evaluated analytically. The device contains a high mobility semiconductor waveguide ring with a high 2-DEG concentration. The device also incorporates a superconducting control line for the magnetic flux application and a superconducting ground plane. Fundamental criteria for the construction of the magnetically coupled quantum interference device are clarified in terms of gate drivability and ballistic transport. Analysis indicates that the present device can potentially reach a high switching speed of 0.2 ps/gate.

1. Introduction

Aharonov-Bohm magnetoconductance oscillaion experimentally observed in metal rings[1] and semiconductor rings[2-4] led to a proposal for a quantum interference transistor using an electric field.[5,6] So far, however, very few studies have appeared that address the fundamental criteria or basic problems of hypotheoretical quantum interference devices.

The purpose of the present study is to clarify the requirements for the construction of a magnetically coupled Aharonov-Bohm quantum interference device and evaluate its switching speed analytically.

2. Device structure

We consider a high mobility semiconductor waveguide ring of which two terminals are connected to the source and drain electrodes, and the magnetic flux is applied by a control current line.

In this study, the device structure shown in Fig.1 is introduced, in which a superconducting control line and a superconducting ground plane are incorporated. Due to the magnetic field expulsion effect of the superconductor, or the Meissner effect, the magnetic field generated by the control line is perpendicular to the superconducting ground plane and it penetrates only to the hollow region of the ring. Therefore, flux Φ enclosed by the electron path and equivalently phase shift is the same for all electrons,

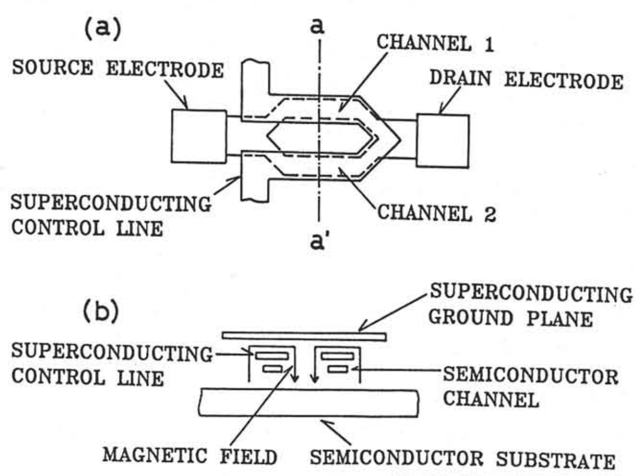

Fig.1. Proposed device structure. (a)Top view. (b)Cross sectional view along aa' line. The vetical structure is as follows: semiconductor channel/insulation layer/superconducting control line/insulation layer/ superconducting ground plane.

resulting in an increased relative conductance change up to 100% in ballistic transport region. Thus, the drain to source current I_{ds} can be modulated up to 100% by the control current I_c as shown in Fig.2.

The circuit configuration considered here is shown in Fig.3. The output current line for firing the next gate consists of the superconducting strip line with characteristic impedance Z_0 , which is terminated in the matching resistor $R_{L2} = Z_0$. For $I_c=0$ (a binary "0"), the drain to source resistance R_{ds} is low. On the other hand, for $I_c=\Phi_0/2/M$ (a binary "1"), R_{ds} is infinitely large.

3. Fundamental criteria for the device construction

To obtain a sufficiently large conductance modulation by the Aharonov-Bohm quantum interference effect, the following conditions are indispensable: 1) ballistic transport[6]: both the inelastic scattering length L_Φ and the elastic scattering length L_0 must be sufficiently larger than the device length L_D, 2) equal branch length of the ring.

In order to obtain a clear understanding of how conductance modulation is modified by elastic scattering in the ballistic transport region, we took into consideration the effect of elastic scattering assuming a simple model, in which an electron suffers a random phase shift Φ_r by elastic scattering. In the region of $L_D < L_0$, an electron suffers elastic scattering with a probability P such that

$$P=1-\exp(-L_D/L_0). \qquad (1)$$

In this random phase shift model, the transmission coefficient D is represented as

$$D = (1/2)(1+\cos(2\pi\Phi/\Phi_0+Q\Phi_r)), \qquad (2)$$

where Q = 1 with a probability P, Q = 0 with a probability 1-P, Φ_r is a random quantity between 0 and 2π, Φ is a flux enclosed by the ring, and Φ_0 =4.14 mV ps is a single flux quantum.

Assuming a small ratio of L_D/L_0 (nearly

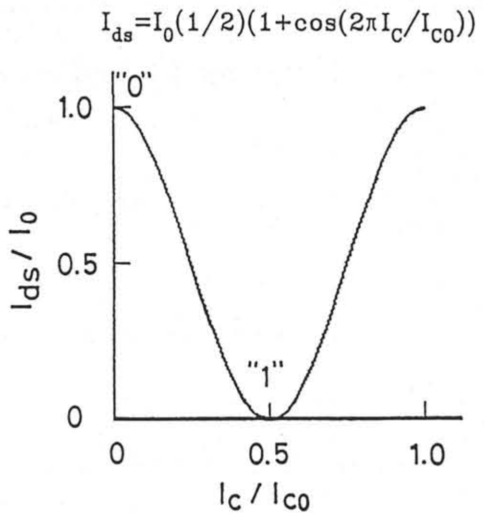

Fig.2. I_{ds} vs I_c. Here, $I_{c0}=\Phi_0/M$, Φ_0 is a single flux quantum, and M is the mutual inductance.

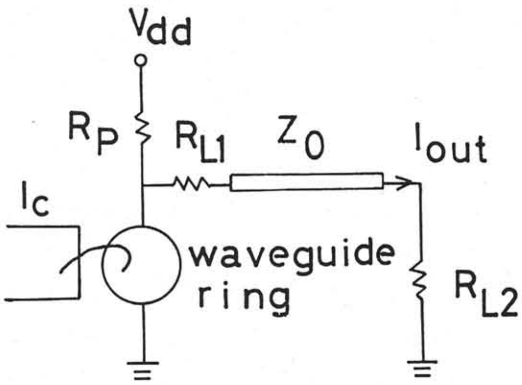

Fig.3. Proposed circuit configuration. The load resistance R_L is the sum of R_{L1} and R_{L2}. The strip line is terminated in the matching resistor $R_{L2} = Z_0$. V_{dd} is the source voltage, and R_p is the source resistor.

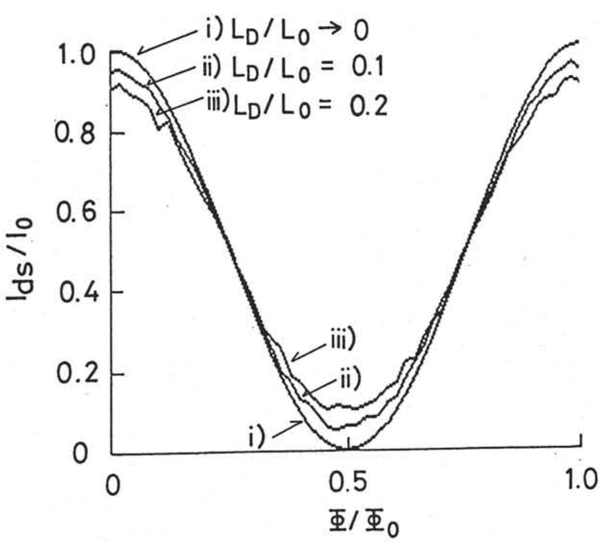

Fig.4. Calculated I_{ds} vs Φ curves for different values of the ratio of L_D/L_0.

ballistic transport), the current was calculated using a tunnel current formula[7] with D expressed by Eq.(2). The calculated results of I_{ds} vs Φ are shown in Fig.4. The results show that the peak current I_p (at $\Phi=0$) decreases in proportion to P and the valley current I_v (at $\Phi=\Phi_0/2$) increases also in proportion to P.

Another restriction for the design is the suppression of the inelastic collision by the optical phonon emission.[6] This restriction sets the upper limit of the drain voltage V_d at less than the optical phonon energy divided by the electron charge, e

We assume an equal branch length $l_1=l_2$ throughout the present study. It is noted, however, that a small difference of l_1 and l_2 greatly reduces the relative conductance change when eV_d is not negligibly small compared with the Fermi energy E_F.

In this study, supposing a switching gate application, requirements for the device construction are considered. A fundamental criterion for a switching device is drivability; that is, the ability of the output current of the gate to drive the latter gate. In the following, it is shown that the requirement for device length follows from the drivability requirement. L_Φ and L_0 will then be discussed in comparison with the obtained device length in terms of ballistic transport.

4. Design and evaluation of the device length

The gate drivability requirement for the present device is represented as

$$I_{out}=(1/2)\Phi_0/M. \qquad (3)$$

Equation (3) basically determines the device length L_D, which is defined as the semicircle length of the waveguide ring. The mutual inductance M is represented as

$$M=L_u(2L_D), \qquad (4)$$

where L_u is the inductance per unit length of the superconducting strip line and is calculated as[8]

$$L_u = (\mu_0/w/K)(h+2\lambda), \qquad (5)$$

where K is the fringing factor, h the insulation layer thickness between the superconducting strip line and the ground plane, and λ is the penetration depth of the superconductor.

The output current I_{out} is proportional to the line width w of each channel of the ring and the maximum current density j_0 through the drain to source,

$$I_{out} \propto wj_0 , \qquad (6)$$

Using Eqs.(3) to (6), it is found that L_D is independent of w and is inversely proportional to j_0 such that

$$L_D \propto \Phi_0/\mu_0/(h+2\lambda)/j_0 . \qquad (7)$$

The numerical factor of Eq.(6) and equivalently Eq.(7) can be determined using the ratio $\alpha=R_L/R_{on}$, where R_L is the load resistance, and R_{on} the drain resistance for "0" state.

j_0 of the ballistic transport region was calculated using the tunnel current formula with D=1. The result is j_0=0.14 mA/µm for the single-hetero-structure AlGaAs/GaAs channel (at 4.2 K, V_d=30 mV) with an electron concentration $n_2=1\times10^{12}$ cm^{-2}. To enhance j_0, a double-hetero-structure was assumed and j_0 =0.24 mA/µm, which is twice the value for a single-hetero-structure. The obtained device parameter R_L for w = 1 µm and α = 1.6 with V_{out}=30 mV is 87 Ω.

The superconducting strip line structure designed here is as follows: 1) a Nb superconducting control line with a width of 1 µm simply taken to be equal to the channel width, 2) a SiO_2 insulation layer with a thickness of 0.85 µm, 3) a Nb ground plane. The calculated parameters for the strip line are as follows: Z_0=57 Ω and L_u=0.402 pH/µm.

Finally, the device length L_D=7.5 µm (corresponding to the ring with a diameter 4.8 µm) was obtained.

For obtaining nearly ballistic transport, we tentatively require L_Φ and $L_0 \geq 5L_D$. To obtain $L_\Phi = v_f\tau_\Phi \sim 40$ μm and $L_0 = v_f\tau_0 \sim 40$ μm with the Fermi velocity $v_F = 0.4$ μm/ps (AlGaAs/GaAs two dimensional electron gas with $n_2 = 1\times10^{12}cm^{-2}$), the inelastic and elastic scattering times, τ_Φ and τ_0, should be ~ 100 ps. τ_Φ increases with decreasing temperature and a τ_Φ of 100 ps has been experimentally obtained for a high mobility AlGaAs/GaAs two dimensional electron gas at 1K.[9] The elastic scattering time of τ_0=100 ps can be obtained for an extremely high mobility $\mu=2.6 \times 10^6$ cm^2/V s AlGaAs/GaAs interface.

5. Gate propagation delay time

The intrinsic switching time t_0 of the present device is $(\Phi_0/2)/V_{out} \sim 0.07$ ps. This is the required time to supply $\Phi_0/2$ flux to the latter gate by the driving voltage V_{out}=30 mV.

The gate propagation delay time t_{pd} is estimated for the gate configuration discussed in section 2. For the present device, it can be shown that the drain to source capacitance C_{ds} is smaller than the total output line capacitance, C. Thus, t_{pd} is approximated by the signal propagation delay time $t_{pl} = L/Z_0 = CZ_0$ in the output line which is composed of the matched transmission line, where L is the total output line inductance. Using Eq.(3) and making L=aM, t_{pl} is represented as

$$t_{pl} = L/Z_0 = a(R_L/Z_0)t_0 \ . \qquad (8)$$

Assuming a=2 and using the values of R_L=87 Ω and Z_0=57 Ω, we obtain a high switching speed of t_{pd}=0.2 ps/gate in the present device.

6. Conclusion

A magnetically coupled Aharonov-Bohm quantum interference device consisting of a semiconductor waveguide ring was designed and its performance was evaluated analytically. The device incorporates a superconducting control line for the magnetic field generation and a superconducting ground plane. Due to the Meissner effect, the magnetic field penetrates only to the hollow region of the ring, resulting in an increased conductance modulation up to 100%.

Fundamental criteria for the construction of the present device were clarified in terms of gate drivability and ballistic transport. It was shown that the gate drivability condition leads to the requirement for the device length. It was also shown that the ballistic transport can be ensured by using a high mobility waveguide ring with a high 2-DEG concentration at low temperatures.

Analysis indicates that the present device can potentially reach a high switching speed of 0.2 ps/gate.

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