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Invited

Electron Wave Transistor

Kazuhito FURUYA

Dept. Electrical and Electronic Engineering
Tokyo Institute of Technology
Ookayama, Meguroku, Tokyo 152 Japan

In conventional transistors, the electron interacts with fixed charges in incoherent manner. This paper discusses the coherent interaction between them as a new principle of the transport control. As an example of such interaction, the electron wave diffraction by the transverse grating and its application for the three terminal device are described.

1. INTRODUCTION

Technologies of the precise epitaxy and the ultrafine fabrication enable us to observe the electron wave phenomena in the semiconductor. However, in conventional devices, the electron wave phenomena such as the interference cause only the fluctuation[1] or the noise and may be negative effects. It is because the electron transport is controlled in an incoherent mode.

On the other hand, there is a possibility to build a new device principle based on a coherent interaction. It is very attractive to explore such new class of devices.

In this paper, we discuss a new concept of the transport control of the electron by using the coherent interaction between the electron and fixed charges in the semiconductor. As an example, the electron wave diffraction by the periodic placement of charges and its application for the three terminal device are described.

2. COHERENT AND INCOHERENT INTERACTION BETWEEN ELECTRON AND CHARGES

Let us consider a placement of charges, for example, ionized donor atoms in the semiconductor. Propagating among the charges, the electron wave is scattered by the Coulomb field of charges. All scattering waves from charges are superimposed. These phenomena are not treated by Poisson's equation with the continuous charge density.

When the charge placement is random, the phase relations among the scattering waves are also random to cause no interference. Even in a systematic charge placement, if the electron wave is not sufficiently coherent, the interference does not appear neither. These are the incoherent interaction between the electron and fixed charges. Only under the systematic charge placement and enough coherence of the electron wave, the scattering waves cause remarkable interference. This is a coherent interaction between the electron and fixed charges.

In conventional devices, the incoherent interaction is used to control the electron transport.

For example, in an emitter-base junction of an npn transistor, acceptor atoms with minus charges are placed at random. The electron wave from the emitter is scattered at the charges(Fig.1). The collection of the scattering waves is the reflecting wave at the junction. As a linear combination of the scattered waves, the reflectivity of the electron is obtained as;

$$R = \left| \sum_{j=1}^{M} A \exp(i\, 2\, k\, r_j) \right|^2, \qquad (1)$$

where k is the propagation constant of the electron wave given as $2\pi/\lambda$, λ is the wavelength, M is the number of charges, A is the amplitude of the scattering wave generated by one charge and r_j is the distance of the j-th charge from the reference plane.

Assuming random charge placement, the incoherent reflectivity is;

$$R_{incoh.} = M \, |A|^2. \qquad (2)$$

On the other hand, under the charge placement where the following relations are satisfied.

$$2\, k\, (r_p - r_q) = 2 \pi m, \qquad (3)$$

where p and q are labels of charges and m is an integer. The reflectivity by the coherent interaction is;

$$R_{coh.} = M^2 \, |A|^2. \qquad (4)$$

The coherent reflectivity is much larger than incoherent one when the charge number M is large.

In the npn transistor, we change the number of minus charges, depleted acceptor atoms, in the junction to change the reflectivity of the electron at the junction. The above suggests much efficient control of the electron reflectivity by using the coherent interaction instead of the incoherent one. Thus, there is a possibility to realize ultralow-power and ultrafast semiconductor device based on the coherent interaction.

For the coherent interaction between the electron and charges, we have to place charged atoms in a definite manner instead of the diffusion process. Figure 2 shows a linear placement of donor(acceptor) atoms, that is, donor(acceptor) wire. On this wire, there are electrons(holes) mobile along the wire. We can change the linear density of the charge of the wire by taking out the mobile carriers from the wire to the external circuit. Thus these wires are building blocks to construct the coherent interaction system in the electron wave device.

3. ELECTRON WAVE DIFFRACTION BY TRANSVERSE GRATING

One of the coherent interaction of the electron and charges is the diffraction by the periodic structure, a longitudinal and a transverse grating. Similar ideas using longitudinal and transverse gratings have been proposed by [2] and [3], respectively. An ultimate extrapolation of these ideas has lead to the present concept of the coherent interaction between the electron and each charge.

To show an idea of the electron diffraction, theoretical results[4] for a transverse grating are summarized. By the grating consists of a periodic placement of InP quantum wire in GaInAs;the pitch of 19 nm, the potential energy difference of 0.23 eV and the grating layer thickness of 38 nm, the diffraction efficiency is more than 90 % at maximum and less than 1% at minimum. Figure 3 shows the distribution of the squared absolute value of the wavefunction in the rear of the grating. Gaussian electron beam deflects depending on the electron energy. Thus the deflection can be controlled sensitively.

4. ELECTRON WAVE DIFFRACTION TRANSISTOR

The electron wave diffraction is applied to construct a three terminal device[5] which consists of the emitter with the extractor, the grating and collectors as shown in Fig.4. By applying voltage across the tunneling barrier between the emitter and the extractor, the hot electron propagates toward the grating. The electron propagation is nearly ballistic over the mean-free-path distance, around 200 nm in GaInAs. The grating is located within this distance.

The diffraction efficiency is controlled by the average potential energy of the grating layer which is determined by the input voltage. The collectors 1 collect the diffracted electron, while the collector 2 collects the undiffracted one. Thus currents of the collectors are controlled by the input voltage.

5. CONCLUSION

As a new device principle, the coherent interaction between the electron and each charge is proposed to control the electron transport in the semiconductor. High efficiency of the coherent interaction possibly provides ultralow-power and ultrafast device performance.

For the realization of such attractive electron wave transistor, much advancement is required in the technology of the nanostructure fabrication.

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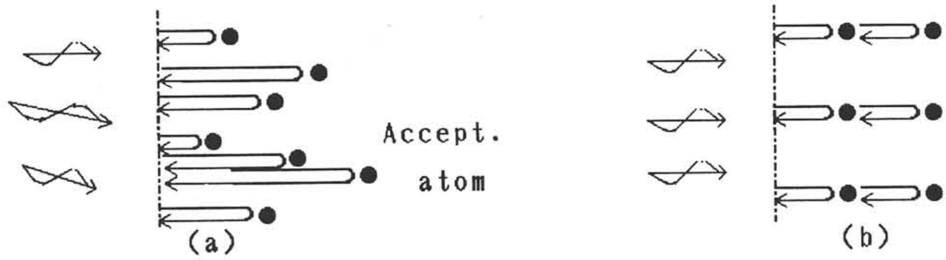

Fig.1 Interaction between electron and charges.
(a)Incoherent mode and (b)coherent mode.

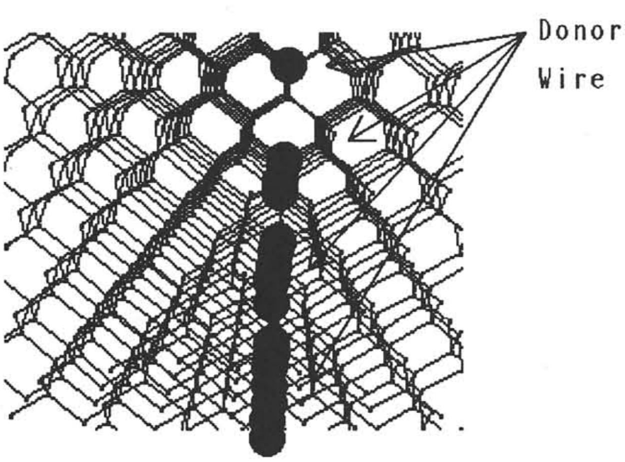

Fig.2 Conceptual scheme of donor wire

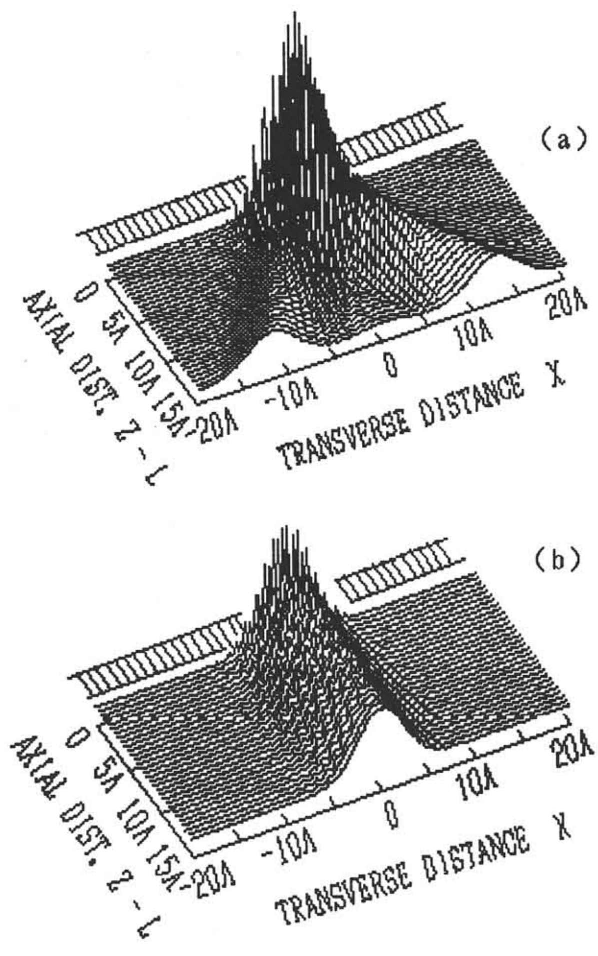

Fig.3
Electron wave diffraction by transverse potential grating
Vertical axis is position probability density $|\psi|^2$. Λ is grating pitch.
Electron energy is
(a)0.25 and (b)0.35 eV.

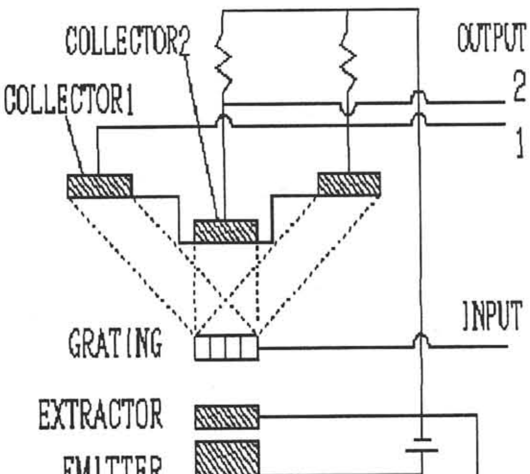

Fig.4 Electron wave
diffraction transistor