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Coherency of Electron Waves in Mesoscopic Electronics

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We investigate the phase breaking mechanisms of electron waves in AlGaAs/GaAs quantum wires by studying systematically the temperature and the hot electron effects on the weak localizations. The phase breaking time τ_ϕ increases with decreasing T, and saturates below ~3 K. It is found that the dominant phase breaking mechanism is the electron-electron scattering when T>3 K. Phonon scattering is shown not to be important in phase breaking process, but effective only in the energy relaxation process. The origin of the saturation in τ_ϕ below 3 K is not clear at present.

1. INTRODUCTION

When a semiconductor device becomes very small, electron wavefunction preserves its phase memory within the structure, and terminal characteristics such as current-voltage relationship reflect the wave nature of electrons. A typical phenomenon is the quantum interference effect of electron waves, which has been of great interest in recent solid state physics[1]. Applications of such quantum interference effect to novel electron devices were also proposed[2]. One of the most important parameters in the quantum interference effect is the phase coherence length, L_ϕ, of electron waves. This is the distance over which the phase of electron wavefunction is preserved. In spite of its importance, there have been only a few experimental reports on L_ϕ in narrow quantum wires.

In this work, we investigate the phase breaking mechanisms of electron waves by studying the temperature and the hot-electron effects on the weak localizations systematically. Although it has been widely anticipated that phonon scattering is the dominant phase breaking mechanism when T>10 K, it is found that frequent electron-electron scattering is dominant in the whole temperature range above 3 K. It is also found that phonon scattering is not important in the phase breaking mechanisms, but effective only in the energy relaxation process.

2. TEMPERATURE DEPENDENCE OF PHASE BREAKING MECHANISMS

It has been widely anticipated that the dominant phase breaking mechanism is electron-electron scattering at low temperatures (<10 K), and that phonon scattering becomes dominant at higher temperatures (>10 K). Although there have been several reports on the temperature dependence of τ_ϕ in quantum wire structures [3,4], the temperature range for measurements was limited mainly from 0.3 K to 4.2 K in the previous experiments. However, if there are more than two competing scattering mechanisms in such a temperature range, the results are not easy to be analyzed. To avoid this, we studied the temperature dependence of τ_ϕ in a rather wide temperature range which extends upto 30 K.

We have fabricated quantum wires from AlGaAs/GaAs modulation doped wafers and determined the width of wires by the conductance[5]. The sample used in this experiment is a gated AlGaAs/GaAs quantum wire with 350 nm width.

Figure 1 shows magnetoconductaces measured at various temperatures ranging from 0.3K to 30K. By fitting the theory of one-dimensional (1D) weak Localizations, we can estimate L_ϕ. We used Beenakker

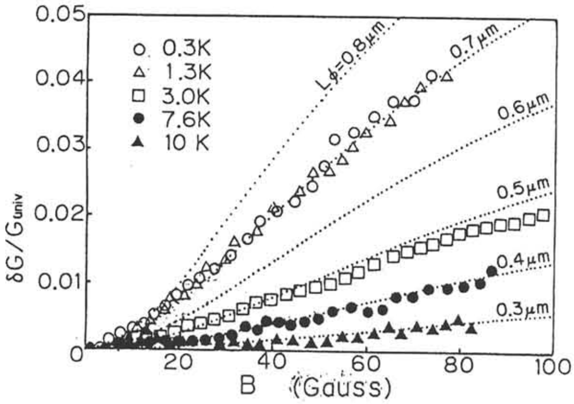

Fig. 1 Magnetoconductance spectra of a gated AlGaAs/GaAs quantum wire (#12) measured at temperatures varying from 0.3K to 10K. The dotted lines show the theoretical fittings of the BvH theory.

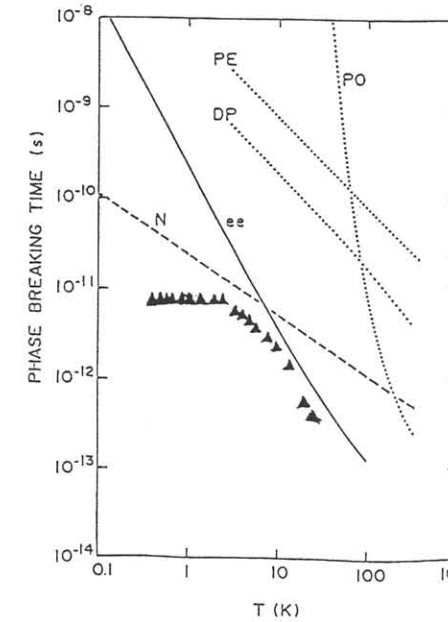

Fig. 2 Temperature dependence of the phase breaking time τ_ϕ. Calculated phase breaking times limited by electron-electron scattering and by phonon scatterings are also shown; DP: deformation potential scattering, PE: piezoelectric scattering, PO: polar optical phonon scattering, ee: momentum-conserving electron-electron scattering, N: scattering by electromagnetic fluctuation.

and van Houten (BvH) theory[6] to deduce L_ϕ. Figure 2 shows the typical temperature dependence of phase breaking time $\tau_\phi = L_\phi^2/D$. The corresponding electron density N_s and the mobility μ are 6×10^{11} cm^{-2} and 2.6×10^4 cm^2/Vs, respectively. τ_ϕ increases with decreasing temperature, but becomes constant below ~3 K.

First, we calculated the phase breaking time limited by phonon scatterings. In the figure, calculated inelastic scattering times limited by phonon scatterings (DP: acoustic deformation potential scattering, PZ: piezoelectric scattering, PO: polar optical phonon scattering)[7] are shown by dotted lines. It should be noted here that τ_ϕ obtained experimentally is in the range from 0.1 ps to 10 ps, while the dephasing time limited by phonon scattering is almost two orders of magnitude longer. This fact is very different from what has been anticipated, and strongly suggests that electron-electron scattering is still dominant even at high temperatures above 10 K.

In order to check this, we calculated the phase breaking time limited by electron-electron scattering. Since $\hbar/k_B\tau_m$=8 K in the present case, both momentum-conserving (pure limit) and momentum-nonconserving (dirty limit) prosesses are expected to be important in the temperature range studied here[8,9]. Here, $\hbar$ is the reduced Planck constant, k_B the Boltzmann constant, τ_m the momentum relaxation time. The calculated phase breaking time limited by momentum-conserving inelastic electron-electron scattering (τ_{ee}) are plotted by a solid line in the figure. In the figure also shown by a broken line is the calculated phase breaking time limited by scattering by electromagnetic fluctuation (τ_N) [momentum-nonconserving], the theory of which was developed for 1D dirty metal systems by Al'tshuler et al.[10].

The agreement between the experimental τ_ϕ and τ_N is reasonably good in the temperature range between 3 K and 10 K, suggesting the importance of the momentum-nonconserving electron-electron scattering process in this temperature range. However, the discrepancy between the experimental results and the theoretical prediction becomes appreciable at lower temperatures. The saturation of τ_ϕ for T<3 K is not caused by electron heating as shown in the next section. This fact suggests that some temperature-independent phase-breaking mechanisms other than the electron-electron scattering are present at low temperatures. A possible mechanism for the saturation is the spin-flip scattering. In metal wires, the saturation of τ_ϕ was attributed to the spin-flip scattering by residual magnetic impurities. Although in the present samples the density of magnetic impurities is negligible, defects with lone pairs introduced by ion implantation might act as magnetic impurities. The other possibility is the scattering by external electromagnetic noise, as discussed by Al'tshuler et al.[10]. This calls for further refinement of the experiment.

At higher temperatures, τ_ϕ decreases approximately as T^{-2} with increasing T. This temperature dependence is what is predicted for momentum-conserving electron-electron scattering in pure metals. In fact, τ_ϕ for T>10 K is in good agreement with calculated τ_{ee} [8,9]. This fact indicates that in high mobility AlGaAs/GaAs quantum wire systems the dominant phase breaking mechanism is the momentum-conserving electron-electron scattering at temperatures above 10 K. For the complete understanding of the phase breaking mechanisms in the whole temperature range, we call for further refinement both in theories and in experiments.

3. HOT ELECTRON EFFECT ON PHASE BREAKING MECHANISMS

Furthermore, we studied the hot electron effects on the phase breaking mechanism. Magnetoconductance was measured at various probing current levels ranging from 1 nA to 3 μA. The sample (#12) is a 350 nm-wide and 10 μm-long gated AlGaAs/GaAs quantum wire.

Figure 3 shows the determined values of τ_ϕ as functions of input power per electron P_e [7]. τ_ϕ starts to decrease when P_e exceeds 10^{-14}W, indicating that the electron temperature T_e is raised by the external input power. By comparing τ_ϕ in Fig. 2 and that in Fig. 3, we can estimate T_e. For example, T_e for the case of T = 3 K and $P_e = 3.5\times10^{-13}$ W is estimated to be 16 ± 5 K. This electron temperature corresponds to the energy relaxation time of 0.5 nsec, which is comparable to the value expected for 2D electrons in AlGaAs/GaAs heterojunctions by assuming the emission of acoustic phonons [11], as shown in Fig. 4. This energy relaxation time is 500 times longer than τ_ϕ (~1psec), which strongly indicates that the phase breaking mechanism is different from the energy relaxation mechanism and is much more frequent. Hence, we can conclude that the dominant phase breaking mechanism is frequent electron-electron scattering even in the hot electron regime, while phonon scattering is responsible

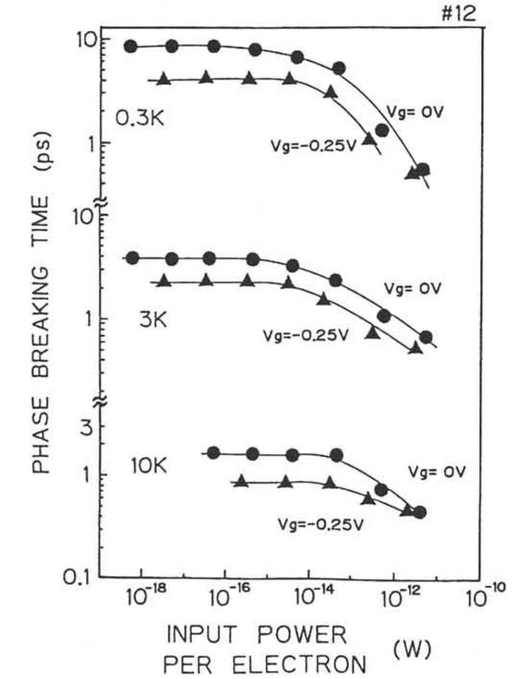

Fig. 3 Phase breaking time τ_ϕ as functions of input power per electron at various lattice temperatures.

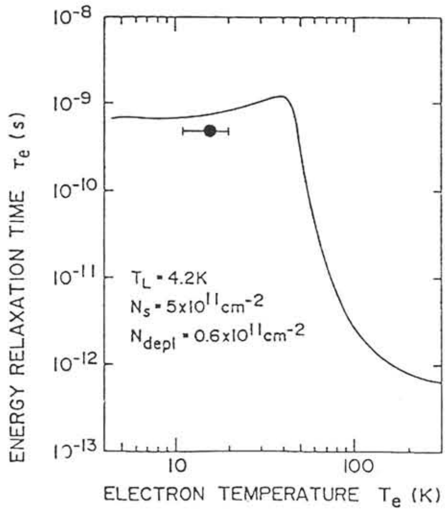

Fig. 4 Calculated energy relaxation time for two-dimensional electrons in a selectively doped AlGaAs/GaAs heterojunction by assuming phonon scatterings. The parameters used in the calculation are shown in the figure. The circle shows the measured energy relaxation time in the AlGaAs/GaAs quantum wire.

only in the energy relaxation process from electron system to phonon system. This energy relaxation mechanism is very important, since it limits the maximum input operation power of the quantum interference transistors[2].

4. CONCLUSION

In this paper, we investigate the phase breaking mechanisms of electron waves in AlGaAs/GaAs quantum wires by studying systematically the temperature and the hot electron effects on the weak localizations. The phase breaking time τ_ϕ increases with decreasing T, and saturates below ~3 K. It is found that the dominant phase breaking mechanism is the electron-electron scattering when $T>3$ K, and that phonon scattering is effective only in the energy relaxation process. The origin of the saturation in τ_ϕ below 3 K is not clear at present.

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