Physica E 6 (2000) 735–737

PHYSICA E

www.elsevier.nl/locate/physe

Electron–electron scattering in two-dimensional electron gas under a controllable spatially modulated magnetic field

Mayumi Kato*, Makoto Sakairi, Akira Endo, Shingo Katsumoto[1], Yasuhiro Iye[1]

Institute for Solid State Physics, University of Tokyo, 7-22-1 Roppongi, Minato-ku, Tokyo 106-8666, Japan

Abstract

Two-dimensional electron gas at GaAs/AlGaAs heterointerface subjected to a lateral magnetic superlattice exhibits a T^2-dependent excess resistivity, which is attributed to electron–electron Umklapp scattering. This has been corroborated by the effect of increased electron temperature. In a sample with an oblique lateral superlattice, the same process gives rise to a transverse component of resistivity. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 73.40; 73.20; 73.20.D

Keywords: Magnetic Weiss oscillation; GaAs/AlGaAs; Lateral magnetic superlattice; Electron–electron scattering; Hot electron

1. Introduction

Electron–electron (e–e) scattering is known to give rise to a T^2-term of resistivity. The T^2-term is observed in various systems such as heavy fermion metals, organic conductors and transition metal oxides, but not in two-dimensional electron gas (2DEG) at semiconductor heterointerface. This is because, in order to contribute to the resistivity, the e–e scattering has to involve the Umklapp process (otherwise the total momentum of two colliding electrons is unchanged) [1]. Since the Fermi circle of a typical 2DEG is much smaller than the Brillouin zone, the Umklapp process cannot occur. When a superlattice with a length scale comparable to the Fermi wavelength is imposed on an otherwise plain 2DEG, the e–e Umklapp process does occur [2].

In the present study, we investigated in 2DEG under the influence of a magnetic lateral superlattice, i.e. a periodic magnetic field modulation [3–5]. We studied the anisotropy of the effect with respect to the direction of modulation wave vector relative to the transport current. We also studied the effect of increased bias current.

2. Experimental

Samples used in the present study were fabricated from a molecular beam epitaxy (MBE) grown GaAs/AlGaAs single heterojunction wafer with

* Corresponding author. Tel.: +81-3-3478-6811(Ext. 5602); fax: +81-3-3401-5169.

E-mail address: mayumi@kodama.issp.u-tokyo.ac.jp (M. Kato)

[1] Also at CREST, Japan Science and Technology Corporation (JST), Japan.

PII: S1386-9477(99)00190-3

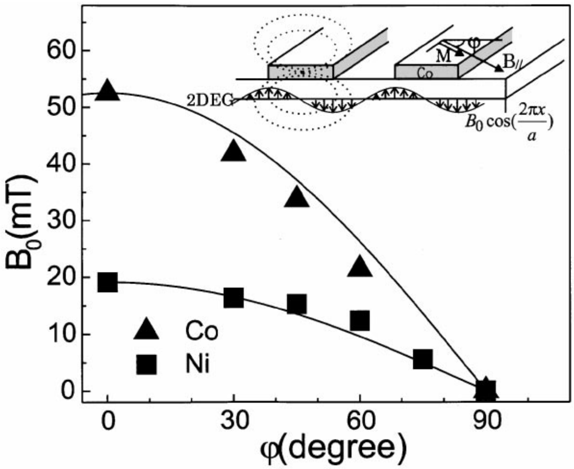

Fig. 1. Inset: schematic illustration of the device. Main panel: φ-dependence of B_0.

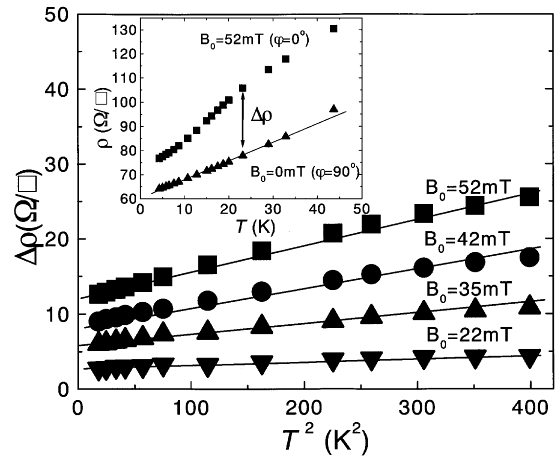

Fig. 2. Inset: $\rho(T)$ for $B_0 = 52$ mT and $B_0 = 0$ mT. Main panel: $\Delta\rho$ plotted against T^2 for different B_0.

electron density $n_e = 2.4 \times 10^{15}$ m^{-2} and mobility $\mu = 60$ m^2 V^{-1} s^{-1} at 4.2 K. The 2DEG plane was at a depth 75 nm from the surface. Samples were patterned in a standard Hall-bar shape by photolithography. A ferromagnetic metal grating with periodicity $a = 500$ nm was fabricated on top of the current channel by electron beam lithography, thermal evaporation and lift-off. The grating was so aligned that the modulation wave vector was parallel to the [1 0 0] direction, in order to minimize the effect of strain-induced piezoelectric potential modulation [6,7]. Transport measurements were carried out by the standard low-frequency AC technique. The ferromagnetic grating was magnetized by an external magnetic field applied parallel to the sample surface. The fringing field creates a sinusoidal magnetic field pattern at the 2DEG plane as shown in the inset of Fig. 1. By changing the azimuthal angle φ of the parallel magnetic field, we can control the modulation amplitude.

3. Results and discussion

The magnetic field modulation amplitude B_0 at the 2DEG plane was estimated from the analysis of the commensurability oscillation of magnetoresistance (magnetic Weiss oscillation).

Fig. 1 shows the φ-dependence of B_0 for two samples with different grating materials (Co and Ni). The $\cos\varphi$-dependence comes from the fact that only the magnetization component parallel to the modulation wave vector is effective in producing the magnetic field modulation. This enables us to vary the modulation amplitude in a single sample. An advantage of using the magnetic field modulation rather than an electrostatic one is that the modulation amplitude can be changed without affecting the electron density. In the present work, we systematically study the resistivity under a modulated magnetic field with zero uniform component.

The temperature dependences of the resistivity for $B_0 = 0$ and 52 mT are shown in the inset of Fig. 2. The data for $B_0 = 0$ shows a T linear resistivity due to the electron–phonon scattering. The difference between the resistivities with and without magnetic field modulation defines the excess resistivity $\Delta\rho$, which represents the extra scattering caused by the spatial modulation. The excess resistivity $\Delta\rho$ is proportional to $\cos^2\varphi$, and hence to B_0^2 [4]. The main panel of Fig. 2 shows the excess resistivity $\Delta\rho$ for different values of B_0 plotted against T^2. The T^2-term is attributed to e–e Umklapp scattering. In the following, we show experiments that reinforce this conclusion.

We fabricated a sample in which the modulation wave vector was at 45° with respect to the current direction, as depicted in the inset of Fig. 3. Solid circles in Fig. 3 show the excess longitudinal resistivity $\Delta\rho_{xx}$ for $B_0 = 52$ mT plotted against T^2. In this oblique superlattice, the e–e Umklapp scattering which gives

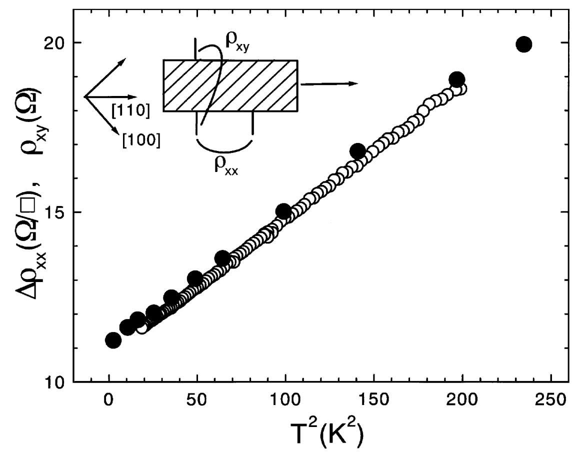

Fig. 3. Inset: schematic illustration of the device. Main panel: $\Delta\rho_{xx}$ (solid circles) and the transverse resistivity ρ_{xy} (open circles) plotted against T^2.

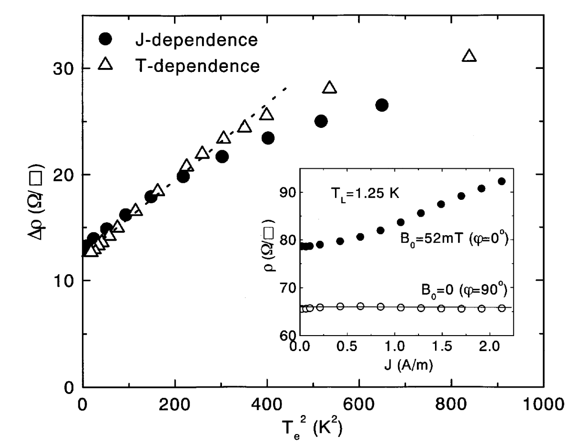

Fig. 4. Inset: J-dependence of ρ for $B_0 = 52$ mT and $B_0 = 0$ mT. Main panel: $\Delta\rho$ plotted against T_e^2 (solid circles) compared with T_L^2 (open triangles)-dependence at low current bias.

rise to $\Delta\rho_{xx}$ also does a transverse resistivity ρ_{xy}. It is seen that the relation $|\rho_{xy}(T)| = \Delta\rho_{xx}(T)$, which is expected for the Umklapp backscattering by a 45° oblique superlattice, holds well. Another sample in which the modulation wave vector was set perpendicular to the current direction showed no excess resistivity [4]. These results establish firmly that the extra scattering is caused by the Umklapp process.

We investigate the hot electron effect at higher current bias. The inset of Fig. 4 shows the resistivity as a function of the current bias J for $B_0 = 0$ and 52 mT at the lattice temperature $T_L = 1.25$ K. The fact that the resistivity for $B_0 = 0$ does not change with J guarantees that T_L remains unchanged. The electron temperature T_e was determined from analysis of the Shubnikov–de Haas amplitude. The main panel of Fig. 4 shows $\Delta\rho$ plotted against T_e^2 (solid circles). It agrees well with the T_L^2-dependence at the lowest current bias (open triangles). This result proves that the effect is governed by the electron temperature, and supports the picture of e–e scattering. We also note that the present result provides a basis for a new method for measuring the electron temperature.

4. Summary

To summarize, we have measured the resistivity of 2DEG samples subjected to magnetic lateral superlattice. The excess resistivity shows T^2-dependence characteristic of e–e scattering. The occurrence of transverse resistivity in an oblique superlattice and behavior at higher current densities are consistent with the e–e Umklapp scattering picture.

Acknowledgements

We thank Prof. H. Fukuyama for helpful conversations.

References

[1] J.M. Ziman, Electrons and Phonons, Clarendon Press, Oxford, 1960.
[2] A. Messica, A. Soibel, U. Meirav, A. Stern, H. Shtrikman, V. Umansky, D. Mahalu, Phys. Rev. Lett. 78 (1997) 705.
[3] M. Kato, A. Endo, S. Katsumoto, Y. Iye, Phys. Rev. B 58 (1998) 4876.
[4] M. Kato, A. Endo, S. Katsumoto, Y. Iye, J. Phys. Soc. Japan 68 (1999) 1492.
[5] N. Overend, A. Nogaret, B.L. Gallagher, P.C. Main, R. Wirtz, R. Newbury, M.A. Howson, S.P. Beaumont, Physica B 249–251 (1998) 326.
[6] E. Skuras, A.R. Long, I.A. Larkin, J.H. Davies, M.C. Holland, Appl. Phys. Lett. 70 (1997) 871.
[7] A. Nogaret, S. Carlton, B.L. Gallagher, P.C. Main, M. Henini, R. Wirtz, R. Newbury, M.A. Howson, S.P. Beaumont, Phys. Rev. B 55 (1997) 16 037.