Solid State Communications, Vol.46,No.7, pp.517-520, 1983.
Printed in Great Britain.

0038-1098/83/190517-04$03.00/0
Pergamon Press Ltd.

DIFFERENTIAL NEGATIVE RESISTANCE CAUSED BY INTER-SUBBAND SCATTERING IN A 2-DIMENSIONAL ELECTRON GAS

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(Received 23 February 1983 by W.Sasaki)

Differential negative resistance has been observed in the range 0.5~1.2 kV/cm at 77 K in a two-dimensional electron gas formed at a modulation-doped AlGaAs/GaAs heterojuction interface. This differential negative resistance is attributed to the sudden onset of inter-subband scattering when electrons achieve sufficient energy from the electric field.

Modulation-doped AlGaAs/GaAs heterojunctions have recently attracted a great deal of interest. They have much higher electron mobilities than bulk GaAs with similar free-electron densities[1]. The enhanced mobility is attributed to the spatial separation of electrons in the GaAs from their donors in the AlGaAs, which reduces the ionized impurity scattering rate. The electrons in the GaAs, transferred from their donors in the AlGaAs, are confined near the interface in a quasitriangular potential well formed by the bending of the energy bands in the GaAs. As these electrons are confined to a narrow space charge region, they behave essentially as a two-dimensional electron gas(2-DEG) and boundary quantization produces discerete electronic subbands[2].

Using the enhanced electron mobilities particularly at low temperature, fast field-effect transistors have been fabricated[3], operating at large electric fields where the mobility is less than its low field value[4,5,6]. While the reduction of mobility with applied electric field has been measured[4,5,6], and is thought to be due to polar optical phonon scattering, the detailed mechanism of this reduction is not fully understood.

In this paper we report electric field dependence of current, electron mobility and sheet electron concentration in the 2-DEG formed at the AlGaAs/GaAs interface. We report differential negative resistance at low electric fields at 77 K, and discuss a possible mechanism for the effect.

A modulation doped AlGaAs/GaAs single heterojunction structure was fabricated on a (001)-oriented Cr-doped semi-insulating GaAs substrate by molecular beam epitaxy. The structure was grown at 700°C and consisted of a 0.8 µm thick undoped GaAs layer and a 0.13µm thick $Al_xGa_{1-x}As$ (x=0.3) layer, doped with Si to a level of 1×10^{18} cm^{-3}, separated by 110 Å of undoped $Al_xGa_{1-x}As$ (x=0.3). A 600 Å thick cap layer of n^+-GaAs was grown on the $Al_xGa_{1-x}As$ layers for good ohmic contact formation.

The sample was photolithographically defined and etched into a 250 µm×50 µm bridge-pattern with two current contacts and six potential probes. The ohmic contacts were formed by vacuum-evaporating Ge-Au-Ni and alloying at 430°C in a hydrogen atmosphere for 2 min.

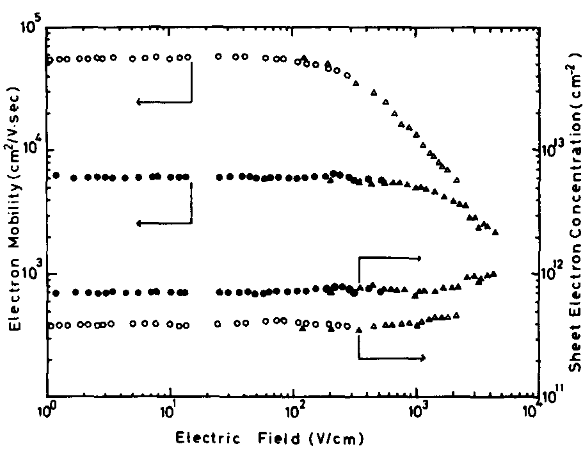

Fig. 1
Electron mobility and sheet electron cocentration vs. electric field curves at 77 K(o,Δ) and 300 K(●,▲).
o,● indicate 7 µsec pulse measurement.
Δ,▲ indicate 300 nsec pulse measurement.

The low electric field Hall mobility and sheet electron concentration were measured by conventional methods and their respective values in the dark were 54,000 cm^2/Vsec and

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3.9×10^{11} cm^{-2} at 77 K and 6,100 $cm^2/Vsec$ and 7.1×10^{11} cm^{-2} at 300 K. The sheet electron concentration increases above 180 K due to some electrons remaining in the doped $Al_xGa_{1-x}As$ layer and current flows in both layers at these temperatures[7].

At 300 K, dc measurements were made up to an electric field of 1 V/cm. At higher fields, pulse measurements were used to avoid sample heating; 7 μsec up to 500 V/cm and 300 nsec up to 2 kV/cm. At 77 K, pulse measurements were made at all electric fields; 7 μsec up to 300 V/cm and 300 nsec up to 4 kV/cm.

Figure 1 shows electron mobility and sheet electron concentration vs. electric field. At 77 K the electron mobility was constant until the electric field reached 100 V/cm when it began to decrease; similarly the sheet electron concentration was constant until 1 kV/cm above which it increased slowly. At 300 K the electron mobility remained constant over a wider electric field, decreasing above 1 kV/cm; the sheet electron concentration increasing at the same electric field as at 77 K.

The current and drift velocity vs. electric field chracteristics are shown in Fig.2; the dashed line is the velocity curve and was calculated from Eq.(1),

$$v = \mu(E)E \qquad (1),$$

where $\mu(E)$ is the electron mobility; it is assumed that the Hall factor is 1.0. At 77 K, differential negative resistance and mobility were observed above 0.5 kV/cm in the current curve and the calculated drift velocity curve. The current increased again above 1.2 kV/cm. The peak velocity was 1.4×10^7 cm/sec at 500 V/cm. At 300 K the current saturated at 3 kV/cm and no differential negative resistance was observed.

The threshold electric field of the differential negative resistance is below the expected threshold for real-space-electron-transfer and the Gunn effect. In the case of real-space-electron-transfer, an electron in the GaAs layer must be heated sufficiently to overcome the energy barrier(ΔE=0.3 eV) between $Al_xGa_{1-x}As$ (x=0.3) and GaAs; the expected threshold electric field is 2~3 kV/cm[8]. In the Gunn effect, the threshold electric field is reported to be 3~4 kV/cm[9]. While Keever et al[4] reported a new differential negative resistance in a modulation-doped AlGaAs/GaAs heterostructure in the range of 1~1.5 kV/cm, the physical mechanism of this process has not been explained.

The physical properties of the 2-DEG confined at the AlGaAs/GaAs interface have been studied extensively. Pinczuk et al reported that the single-particle subband excitation can be observed by light scattering experiments and the energy difference between the ground state and first excited state in the electron subband, ε_{01}, is reported to be about 20 meV[10]. The dependence of the electron mobility on sheet electron concentration has been studied, and the mobility reduces suddenly due to the appearance of inter-subband scattering when the sheet electron concentration reaches $7\sim9\times10^{11}$ cm^{-2} and electrons begin to occupy higher subbands[11,12,13]. As the state density of each

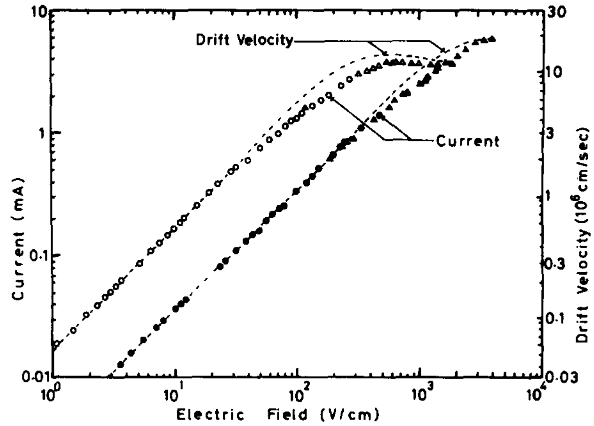

Fig. 2
Electric field dependence of current at 77 K(o,Δ) and 300 K(•,▲), and calculated drift velocity(- - - -).
o,• indicate 7 μsec pulse measurement.
Δ,▲ indicate 300 nsec pulse measurement.

2-DEG subband, $D_2(\varepsilon)$, is 2.8×10^{10} $cm^{-2}meV^{-1}$ in GaAs[14], this threshold concentration indicates that the subband energy difference, ε_{01}, is 24~32 meV. A measurement of electric field induced heating on a modulation-doped multi-quantum well structure shows that the electron temperature increases at very low electric fields and that polar optical phonon scattering is dominant in transferring energy from electrons to the lattice above an electron temperature of 40 K[15]. The effect of the rapid decrease in mobility, shown in Fig.1, has been explained elsewhere[6,15] in terms of hot electron interactions, although without quantitative agreement.

Figure 3 shows the ratio of the mobility decrease and low electric field mobility. The electric field dependence of the mobility, $\mu(E)$, obeys, in the warm electron region, Eq.(2)[16],

$$\mu(E) = \mu_0(1+\beta E^2) \qquad (2),$$

where β is a function only of temperature and μ_0 is low electric field electron mobility. We estimate the warm electron region to be between 100 V/cm and 300 V/cm in Fig.3. In this region, the energy relaxation time, τ_ε, is estimated from Eq.(3),

$$\tau_\varepsilon = \frac{3}{2}kT\,(\beta/\mu_0)(1/r) \qquad (3),$$

where r is the exponent of the energy dependence of the effective momentum relaxation time[16]. In our case at 77K, the exponent r is about -0.4 because of dominant polar optical scattering[17], and β is -3.1×10^{-6} cm^2/V^2 . Substituting r,β and μ_0, the energy relaxation time, τ_ε, in the warm electron region is calculated to be 1.4 psec. This value is thought to be nearly the same at the threshold electric field. The electrons are heated by the electric field and attain an electron temperature, T_e, which is defined by Eq.(4)[16],

$$e\mu(E)E^2\tau_\varepsilon = \frac{3}{2}k(T_e-T) \qquad (4).$$

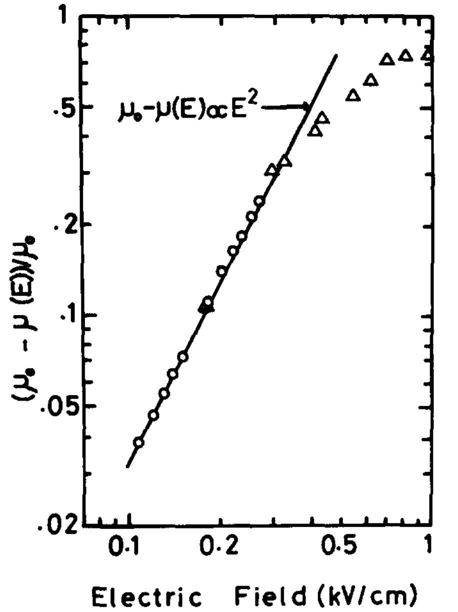

Fig.3
Ratio of mobility decrease and low electric field mobility vs. electric field at 77 K.
o indicate 7 μsec pulse measurement.
Δ indicate 300 nsec pulse measurement.

This relation is valid in the 2-DEG system at 77 K because of the isotropic interaction of phonon and ionized impurity. Substituting the value of μ(E) and τ_ε appropriate at the onset of differential negative resistance, the calculated electron temperature is 12.5 meV(145 K). As our sample has a sheet electron concentration of 3.9×10^{11} cm^{-2}, corresponding to a Fermi energy of 13.1 meV, the electron gas does not reach the higher subband.

When the electron acquires sufficient energy to reach the higher subband, there is a sudden reduction of the electron mobility[11,13]. In this reduction of electron mobility, elastic scattering, such as scattering by residual ionized impurities in the GaAs, plays an important role. Scattering by ionized impurities may be responsible for the reduction in the electron mobility of our sample to 54,000 cm^2/Vsec at 77 K. Since elastic scattering does not change the electron energy, the scattering rate reflects the step-function 2-DEG state density and increases when electrons are able to reach the higher subband and elastic scattering between subbands can occur. This onset of inter-subband scattering causes the current reduction resulting in differential negative resistance. The differential negative resistance occurs when the electrons begin to reach the higher subband with the additional electron energy, 12.5 meV, due to the heating by the electric field. That is, the sum of the Fermi energy and electron temperature exceeds the subband energy difference, ε_{01}.

The relation of the sheet electron concentration, n_s, and the threshold electric field can be found from Eq.5,

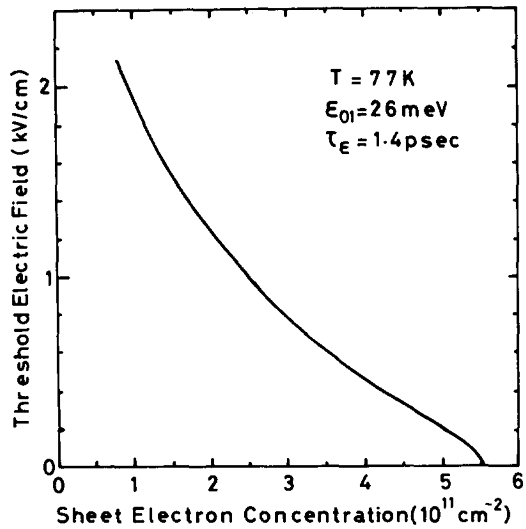

Fig.4
Calculated threshold electric field vs. sheet electron concentration characteristic using Fig.1.

$$\varepsilon_{01} = \varepsilon_f + kT_e \qquad (5),$$

where ε_f is the Fermi energy and the electric field dependence of T_e can be calculated from Eq.4. In a 2-DEG system the Fermi energy can be expressed by Eq.6[14],

$$\varepsilon_f = kT \ln(\exp(n_s/(D_2(\varepsilon)\ kT) - 1)) \qquad (6),$$

and is 13.1 meV for our sample at 77 K. The n_s dependence of the threshold electric field, calculated with the assumption that the subband energy difference, ε_{01}, is 26 meV and is independent of n_s, is shown in Fig.4. The slope of the curve is approximately 300~800 V/cm per 1.0×10^{11} cm^{-2}. The threshold electric field is very sensitive to the concentration, temperature, and subband energy difference. This sensitivity implies that negative differential resistance can only be observed under special condition and that threshold electric fields will vary from sample to sample. A similar mechanism has been studied in the voltage controlled differential negative resistance in Si MOS inversion layers which also exhibit 2-DEG properties[18,19].

At 300 K electrons remain in the AlGaAs layer and current flows both in the two-dimensional layer and the AlGaAs. The electron thermal energy exceeds the subband energy difference, and differential negative resistance is not observed.

In conclusion, we report the observation of differential negative resistance caused by the sudden onset of inter-subband scattering in a 2-DEG system at the AlGaAs/GaAs interface at 77 K. The inter-subband scattering occurs when electrons achieve sufficient energy to be excited to the upper subband. We have discussed the threshold electric field of the differential negative resistance and calculated the dependence of the threshold electric field on the sheet electron concentration .

Acknowledgement

The authors wish to thank Y.Horikoshi, S.Hashimoto and N.Kuroyanagi for their continual encourgement. A.Livingstone is grateful for a Fellowship jointly sponsored by British Telecom and the UK Department of Industry "Visiting Engineers Scheme."

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