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Electron Transport in GaAs Quantum Wells: Effect of Interface Roughness Scattering

Rita GUPTA
School of Engineering, University of Hull, Hull HU6 7RX, UK

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Abstract

The importance of interface roughness (IFR) scattering of electrons and LO-phonons for electron transport in semiconductor quantum wells is discussed. Modulation doping of quantum wells minimizes the effect of impurity scattering on the low-field electron mobility so that IFR scattering of electrons in the well becomes the major limiting factor. A model calculation of IFR scattering of electrons in quantum wells is presented and it is shown that (both)Λ and Δ, the parameters defining IFR, can be estimated by comparing the theoretical and experimental electron mobilities.

The application of high electric field leads to a distribution of hot electrons which relax their energy and momentum through the emission of LO phonons. The dynamics of this non-equilibrium distribution of LO phonons greatly influences the electron transport at high fields. For example, a rapid momentum relaxation of hot LO phonons can lead to the saturation of electron drift velocity at high electric fields. Various mechanisms for momentum relaxation of LO phonons are presented and it is shown that IFR scattering is a major contributor to the non-drift of hot phonons. Implications for high-field electron transport in GaAs/AlGaAs quantum wells are discussed.

1. Introduction

The inevitable presence of interface roughness (IFR) in multiple quantum wells (MQWs) and heterostructures can lead to some undesirable effects on the performance of optical and electro-optic devices. For example it can cause splitting or broadening of the exciton spectra [1,2] in these systems. Also, scattering of electrons from IFR limits the low-field electron mobility [3], and the IFR scattering of LO phonons, generated at high fields, can render the hot phonon population non-drifting. This leads to the saturation of high-field electron drift velocity [4]. In modulation doped MQWs an undoped spacer layer generally separates the quantum well from the doped region in the barrier. Therefore, the scattering of electrons from remote charge impurities is negligible and low-field mobility is mainly limited by IFR scattering. [5]

The well-width dependence of the effect of IFR on low-field electron mobility has been discussed in the past: Sakaki et al. [6] considered IFR scattering in an infinite quantum well and obtained a L^{-6} dependence. The dependence is expected to be less strong for finite quantum wells, as discussed by Gupta and Ridley [5], since $\partial E/\partial L$ is less than L^{-3} in these systems and also not all of the electron wavefunction is contained within the well. However, in the real world, it is meaningful to discuss the well-width dependence of interface roughness scattering only if the two parameters Δ and Λ describing the IFR are assumed to be constant throughout. We have demonstrated [7] from our measurements on various GaAs/AlGaAs MQWs, that not only do Δ and Λ, the width and the lateral size of the interface roughness, respectively, vary from wafer to wafer but also for different samples made from the same wafer. It is also found that the experimental results of other groups [8,9] can be explained by a reasonable flexibility in Δ and Λ.

This paper is organised as follows: Section 2 outlines the calculation of the contribution of interface roughness scattering to the low-field electron mobility, and section 3 presents a procedure for estimating the magnitude of interface roughness present. Section 4 gives a synopsis of high-field longitudinal transport in semiconductors and discusses the role of IFR scattering in shaping the high-field dependence of electron drift velocity. The results and discussion are summarised in Section 5.

2. Low-field electron mobility

Low-field electron mobility in quantum well structures is mainly determined by scattering of electrons from charge impurity centres and from well-width and alloy fluctuations at the interface. However, most MQW devices are modulation doped with an undoped spacer layer separating the quantum well from the donors, so that the effect of charged impurity scattering is minimal. Below we present a calculation of the mobility of electrons scattering from the interface roughness which has in general been described in terms of a Gaussian distribution of the lateral size (Λ) and a width (Δ) of the interface roughness [6], i.e.,

$$\langle \Delta(\mathbf{r})\Delta(\mathbf{r}')\rangle = \Delta^2 \exp[-(\mathbf{r}-\mathbf{r}')^2/\Lambda^2] \tag{1}$$

where $\mathbf{r}$ and $\mathbf{r}'$ are the two-dimensional spatial co ordinates. Therefore, the momentum relaxation rate for electrons being scattered from IFR is obtained as

$$W_e = m^*(\partial E/\partial L)^2\Delta^2\Lambda^2 Z_e(k,\Lambda)/8\pi^2 h^2, \tag{2a}$$

where

$$Z_e(k,L) = \int (1-\cos q)\exp[-k^2\Lambda^2\sin^2(\theta/2)]d\theta/[S(2k\sin(\theta/2),T)], \tag{2b}$$

m^* is the electron effective mass, h is the Plank constant, E is the energy of the confined electron, L is the quantum well-width, and S(q,T) is the temperature dependent screening factor. The integration in Equation (2b) is from 0 to 2π. Since this section is concerned with low-temperature mobilities, $T = 0$ is assumed. The IFR-limited electron mobility $\mu_t = e\tau_t/m^* = e/W_e(k_F)m^*$ may thus be calculated.

3. Theory: Estimation of the interface roughness parameters for the samples

From Eq. (2) it is seen that the momentum relaxation rate for electrons scattering from IFR is a double function of Λ. Also, the IFR scattering of low wavevector electrons is screened out. Sakaki et al. [6] estimated the value of Λ by matching the temperature dependence of the transport mobility, where $\Delta = 1$ monolayer (ML) was assumed. In addition to the transport mobility μ_t we have also calculated the electron quantum mobility m_q which is obtained by replacing the factor $(1 - \cos)$ by 1 in Eq. (2b). Figure 1 shows the Λ-dependence of the IFR scattering limited quantum and transport electron mobilities, m_q and m_t, respectively, for well-width $L = 50$, $n_{2d} = 3.10^{11}$ cm^{-2} and $\Delta = 1$ monolayer (ML). The variation of the ratio μ_t/μ_q with Λ is shown in Figure 2 for electron densities $3 \cdot 10^{11}$ cm^{-2} and 7.10^{11} cm^{-2} It is seen that the transport-to-quantum mobility

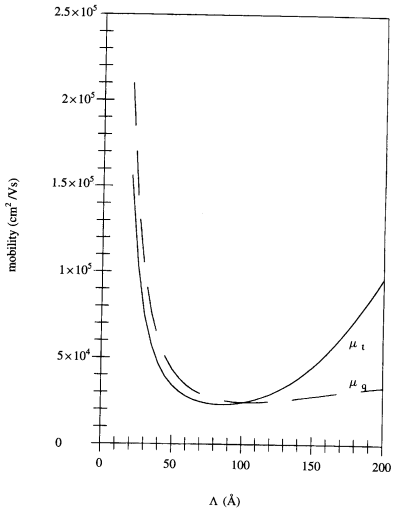

Figure 1. Interface roughness scattering limited transport and quantum mobilities versus the lateral size of one monolayer ($\Delta = 1ML$) fluctuation. $L = 50$, $n_{2D} = 3.0x10^{11}$ cm^{-2}.

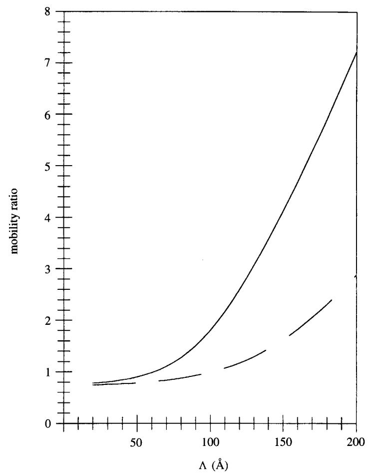

Figure 2. The ratio of the interface roughness scattering limited transport mobility to quantum mobility versus the lateral size of the monolayer fluctuation. $L = 50$, $\Delta = 1$ ML. Solid curve, $n_{2D} = 7.0x10^{11}$ cm^{-2}; broken curve, $n_{2D} = 3.0x10^{11}$ cm^{-2}.

ratio increases with increasing Λ and electron concentration. Figure 3 presents the dependence of μ_q and μ_t on n_{2d} for $\Lambda = 70$, the values of L and Δ being the same for all figures. It is seen from Figures 1, 3 that unique values of Λ and Δ may be obtained by matching both the calculated mobilities $\mu_q(\Lambda, \Delta)$ and $\mu_t(\Lambda, \Delta)$ with the measured quantum and transport mobilities, μ_q and μ_t, respectively. This procedure has been followed for a number of samples [7] and the values of Λ and Δ obtained range from 100-300 and from 2-3 monolayers, respectively.

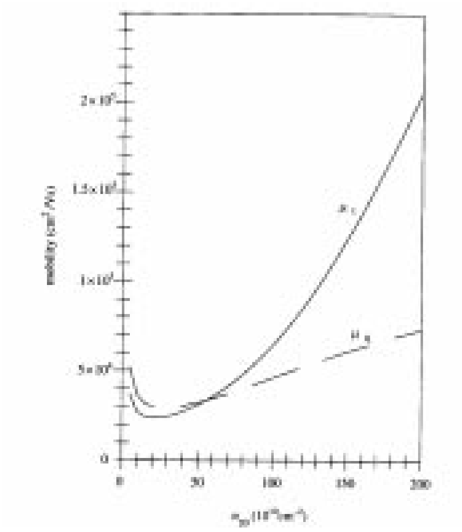

Figure 3. Interface roughness scattering limited transport and quantum mobilities versus 2D electron density. $L = 50$, $\Delta = 1ML$, $\Lambda = 70A$

4. IFR and high-field electron transport

Electron transport at high electric fields in semiconductors is dominated by electron-LO phonon scattering which is described by the Fröhlich interaction Hamiltonian H_p. The rate of emission (or absorption) of LO phonons by an electron, t_0, is calculated from H_p. For nominally doped GaAs this rate is $\tau_0 \sim 1/130 fs^{-1}$.

4.1. Energy and Momentum Relaxation of Electrons.

Electrons gain energy in an applied electric field which is dissipated to the lattice via the emission of LO phonons. The rate of emission of LO phonons is usually an order of magnitude faster than the rate of decay of these phonons. For example, the lifetime of the LO phonon in GaAs has been measured to be ~5-7 ps [10], more than an order of magnitude greater than τ_0. This relatively large phonon lifetime results in a non-equilibrium population of LO phonons at high fields which can be re-absorbed by the electrons, thus reducing the electron energy relaxation rate. The energy loss rate for electrons at temperature T is

$$W_E = (\hbar\omega_{LO}/\tau_{eff})\exp[-\hbar\omega_{LO}/k_BT], \quad (3)$$

where W_E, $\hbar\omega_{LO}$ and τ_{eff} are the power input per electron, LO phonon energy and the electron-LO phonon scattering time. In the absence of any hot phonons the electron-phonon scattering should be the same as that for undoped semiconductor (~130 fs for GaAs). However, it has been demonstrated that the measured value of τ_{eff} in modulation doped GaAs/AlGaAs quantum wells is an order of magnitude larger [4]. This decreased phonon emission rate, which is found to be proportional to the bulk electron density in the well, is a signature of the presence of hot LO phonons at high electric fields.

The effect of hot phonons on the momentum relaxation of electrons (electron drift velocity) depends on the condition of the sample under study. The LO phonons emitted in a high electric field have momentum in the direction of the field and are known as drifting phonons. If the phonon is not elastically scattered between its emission and re-absorption, both energy and momentum are returned to the electron system and both relaxation rates are reduced. In this case large high-field electron drift velocities are to be expected. If, on the other hand, the elastic scattering of phonons is faster than $1/\tau_{eff}$ then the re-absorbed phonon returns its energy but not the momentum to the electron system. The phonons are non-drifting in this case and a saturation of electron drift velocity at high fields is observed. Various mechanisms for elastic scattering of LO phonons in two-dimensional semiconductors have been discussed [5]. It has been found that IFR scattering is the most important factor determining the non-drift of hot LO phonons, especially for GaAs quantum wells where the alloy scattering contribution is absent. Therefore, only the scattering of phonons is discussed below.

4.2. Elastic scattering of phonons from IFR

The frequency of the optic phonon depends on the quantum well-width through the dispersion relation

$$\omega^2 = \omega_0^2 - \nu_s^2(q^2 + q_z^2) \quad (4)$$

where $q_z = n\pi/L$ and is the frequency of the mode at the zone centre. Therefore the perturbation to the phonon frequency due to well-width fluctuation of width Δ is

$$\delta\omega^2(phonon) = \nu_s^2 n^2 \langle\Delta\rangle/\omega L^3 \quad (5)$$

Assuming the Gaussian distribution for the interface roughness (Eq.(1)), the Hamiltonian for the interaction of IFR with the phonon becomes

$$|H| = (\pi h^2/4A)\delta\omega^2 \cos^2\theta\Lambda^2 \exp[-\delta q^2\Lambda^2/4], \quad (6)$$

where $dq = 2q \cdot \sin(\theta/2)$ for the elastic processes considered here. The corresponding phonon momentum relaxation rate is then obtained as

$$W_{ph} = n^4 \pi^4 \nu_s^2 \Delta^2 \Lambda^2 Z_p / (2\omega_0 L^6), \tag{7a}$$

where

$$Z_p(k, L) = \int (1 - \cos\theta) \cos^2\theta \exp[-q^2 \Lambda^2 \sin^2(\theta/2)] d\theta. \tag{7b}$$

Figure 4 shows the well-width dependence of phonon momentum relaxation times, $\tau_{ph} = 1/W_{ph}$, for interface roughness parameters $\Lambda = 70$ and $\Delta = 1$ monolayer. Scattering times of ~ 1 ps or less are seen for narrow wells. The presence of alloy fluctuations at the interface will perturb the phonon frequency w through the fluctuation of the atomic masses involved and thus lead to phonon scattering. However, this effect is found to be comparatively weaker [5].

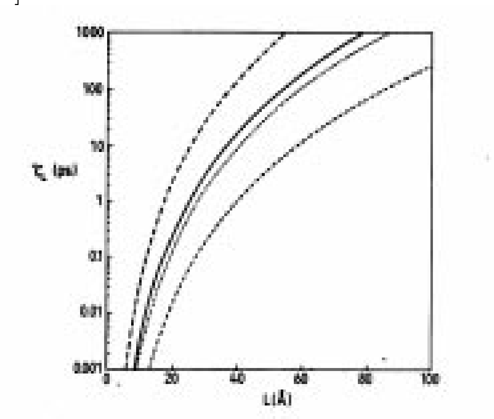

Figure 4. Momentum relaxation times for confined phonons (n = 1, 2), scattering from well-width fluctuations, in GaAs well for $\Lambda = 70$ and $\Delta = 2.83$. $-----$, $n = 1$, $q = 5x10^5$ cm^{-1}; $\sim\sim$, $n = 1$, $1 = 2.5x10^6$ cm^{-1}; $-----$, $n = 2$, $1 = 5x10^5$ cm^{-1}; and $\ldots$, $n = 2$, $q = 2.5x10^6$ cm^{-1}.

5. Summary of results and discussion

The effect of interface roughness (both well-width and alloy fluctuation) on electron transport in modulation doped GaAs MQWs has been discussed. It has been shown that the quality of the interface determines both the low-field mobility and high-field electron drift velocities that can be achieved. A method for estimating the width and the lateral size of interface roughness present in semiconducting materials has been outlined when both the transport and quantum mobilities are known.

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