

# Effects of interface roughness and phonon scattering on intersubband absorption linewidth in a GaAs quantum well

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We experimentally and theoretically study the effects of interface roughness and phonon scattering on intersubband absorption linewidth in a modulation-doped GaAs/AlAs quantum well. Quantitative comparisons between experimental results and theoretical calculations make it clear that interface roughness scattering is the dominant scattering mechanism for absorption linewidth in the temperature range below 300 K. Even at room temperature, phonon scattering processes contribute little to linewidth, while polar-optical phonon scattering limits electron mobility.

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Intersubband absorption linewidth in a quantum well (QW) has been said to have little correlation with electron mobility. Campman *et al.* reported that linewidth is sensitive to interface roughness scattering, while it is not to alloy scattering, to which mobility is sensitive.<sup>1</sup> In addition to ionized impurity scattering<sup>2</sup> and band nonparabolicity,<sup>3</sup> the collective nature of intersubband transition and its effect on linewidth at high electron concentrations have been revealed by Warburton *et al.*<sup>4</sup> It is also interesting that quite narrow linewidths have been reported for a particular double QW system.<sup>5</sup> As a whole, systematic and quantitative understanding of absorption linewidth has not yet been achieved, which is in contrast to the case of mobility.<sup>6,7</sup>

In this letter, we investigate the effects of interface roughness and phonon scattering on absorption linewidth in a GaAs QW. We measure linewidth in comparison with mobility in a modulation-doped GaAs/AlAs QW at temperatures ranging from 4.5 to 300 K, which are indeed different in terms of both absolute values and temperature dependence. Theoretical analysis shows that linewidth is one order of magnitude more sensitive to interface roughness scattering than mobility, but that linewidth is less sensitive to phonon scattering. We obtain good agreement between the experimental results and theoretical calculations for both linewidth and mobility.

The sample used in this study was a modulation-doped GaAs single QW with AlAs barriers grown by molecular beam epitaxy. The QW structure consisted of a Si-doped Al<sub>0.3</sub>Ga<sub>0.7</sub>As layer, a 50 Å undoped Al<sub>0.3</sub>Ga<sub>0.7</sub>As spacer, a 50 Å undoped AlAs barrier, an 80 Å undoped GaAs QW layer, a 50 Å undoped AlAs barrier, a 50 Å undoped Al<sub>0.3</sub>Ga<sub>0.7</sub>As spacer, and a Si-doped Al<sub>0.3</sub>Ga<sub>0.7</sub>As layer, as shown in the inset of Fig. 1. In the growth process, a growth interruption was used at the AlAs-on-GaAs interface for smoothing. The mobility  $\mu$  and the sheet electron concentration  $N_s$ , deter-

mined by Hall measurement, were  $2.9 \times 10^4$  cm<sup>2</sup>/Vs and  $9.8 \times 10^{11}$  cm<sup>-2</sup> at 4.2 K, respectively.

The structure was chosen so that roughness scattering at the GaAs-on-AlAs interface would dominate the electron mobility at low temperatures,<sup>8</sup> and that polar-optical (LO) phonon scattering would do so at room temperature.<sup>7</sup> The effect of ionized impurity scattering was reduced by the 100 Å spacer layers, and the influence of alloy scattering was absent because of the GaAs QW with AlAs barriers.

The sample was processed into a 3-mm-long waveguide structure with a thickness of 0.3 mm. Both ends were polished at 45° so that the light incident to the face could be reflected at the top and bottom surfaces of the waveguide. Aluminum (100 nm thick) was evaporated onto the top surface to serve as a gate for modulating the electron concentration in the QW. Absorption spectra were measured at temperatures  $T=4.5$ –300 K with a Fourier transform infrared spectrometer and microscope ( $\mu$ -FTIR). By modulating the electron concentration between the accumulation and depletion conditions, and detecting signals with a lock-in technique, we obtained background-free absorption spectra with high signal-to-noise ratios to measure the linewidth precisely.

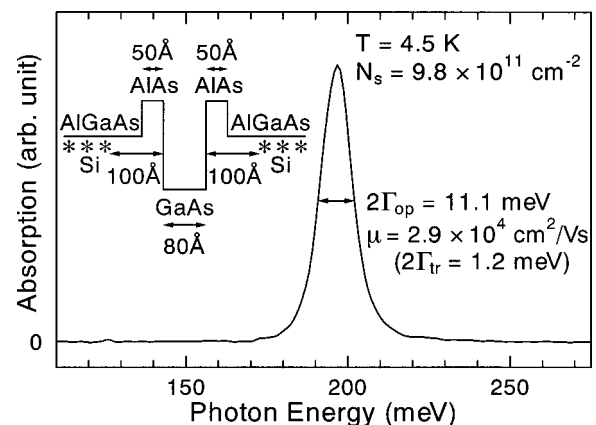


FIG. 1. An intersubband absorption spectrum of a GaAs/AlAs single QW observed at 4.5 K with a  $\mu$ -FTIR via a modulation technique. The inset represents the structure of this sample.

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Figure 1 shows an observed absorption spectrum at 4.5 K. The full width at half maximum of the absorption, denoted hereafter as  $2\Gamma_{\text{op}}$ , was 11.1 meV. To compare this value with mobility, we defined transport energy broadening as  $2\Gamma_{\text{tr}} = 2\hbar/\langle\tau_{\text{tr}}(E)\rangle = 2\hbar e/\mu m^*$ . Here,  $e$  is the elementary charge,  $\hbar$  is the reduced Planck constant,  $m^*$  is the electron effective mass,  $\tau_{\text{tr}}(E)$  is the momentum relaxation time of electrons, and the brackets denote an average over energy.<sup>8</sup> From the low-temperature mobility of  $\mu = 2.9 \times 10^4 \text{ cm}^2/\text{V s}$ , we obtained  $2\Gamma_{\text{tr}} = 1.2 \text{ meV}$ . Note that the linewidth  $2\Gamma_{\text{op}}$  was about an order of magnitude larger than the transport broadening  $2\Gamma_{\text{tr}}$ .

To explain the low-temperature values of the linewidth  $2\Gamma_{\text{op}}$  as well as the transport broadening  $2\Gamma_{\text{tr}}$ , or the mobility  $\mu$ , we numerically calculated the most probable contribution of interface roughness scattering using Ando's theory.<sup>6,9,10</sup> Ando's theory is based on the single-particle picture, which is applicable when the depolarization shift is small compared with linewidth. This was the case in our experiment, where  $N_s = 9.8 \times 10^{11} \text{ cm}^{-2}$  gives a depolarization shift of about 5 meV.

According to Ando's theory, the intersubband absorption line shape for elastic scattering processes can be expressed as

$$\text{Re } \sigma_{zz}(\omega) \propto \int dE f(E) \frac{\Gamma_{\text{op}}(E)}{(\hbar\omega - E_{10})^2 + \Gamma_{\text{op}}(E)^2}, \quad (1)$$

$$\Gamma_{\text{op}}(E) = \frac{1}{2} [\Gamma_{\text{intra}}(E) + \Gamma_{\text{inter}}(E)]. \quad (2)$$

Here,  $\omega$  is the photon frequency,  $f(E)$  is the Fermi distribution function,  $E_{10}$  is the intersubband energy separation,  $\Gamma_{\text{intra}}(E)$  is the width due to the difference in intrasubband scattering matrix elements for the ground and first excited subbands, and  $\Gamma_{\text{inter}}(E)$  is the width due to the intersubband scattering.<sup>9</sup>

Using a roughness model that characterizes the GaAs-on-AlAs interface by the Gaussian autocorrelation function with a mean height of  $\Delta$  and a correlation length of  $\Lambda$ ,<sup>6,8</sup> we have

$$\Gamma_{\text{intra}}(E) = \frac{m^* \Delta^2 \Lambda^2}{\hbar^2} (F_{00} - F_{11})^2 \int_0^\pi d\theta e^{-q^2 \Lambda^2/4}, \quad (3)$$

$$\Gamma_{\text{inter}}(E) = \frac{m^* \Delta^2 \Lambda^2}{\hbar^2} F_{01}^2 \int_0^\pi d\theta e^{-\tilde{q}^2 \Lambda^2/4} \quad (4)$$

with  $F_{mn} = \sqrt{(\partial E_m / \partial L)(\partial E_n / \partial L)}$ . Here,  $L$  is the well width,  $E_n$  is the quantization energy of the  $n$ th subband,  $\theta$  is the scattering angle, and  $q$  and  $\tilde{q}$  are the absolute values of the two-dimensional scattering vector in the "intra" and "inter" processes,<sup>9</sup> given by

$$q^2 = \frac{4m^*}{\hbar^2} E(1 - \cos \theta), \quad (5)$$

$$\tilde{q}^2 = \frac{4m^*}{\hbar^2} \left[ E + \frac{E_{10}}{2} - \sqrt{E(E + E_{10})} \cos \theta \right], \quad (6)$$

respectively. In Eq. (3), a screening factor that appeared in the original theory<sup>9</sup> is omitted because its contribution is negligible in the following analysis.

We have a similar expression for the transport energy broadening  $2\hbar/\tau_{\text{tr}}(E)$ , which is expressed as<sup>8</sup>

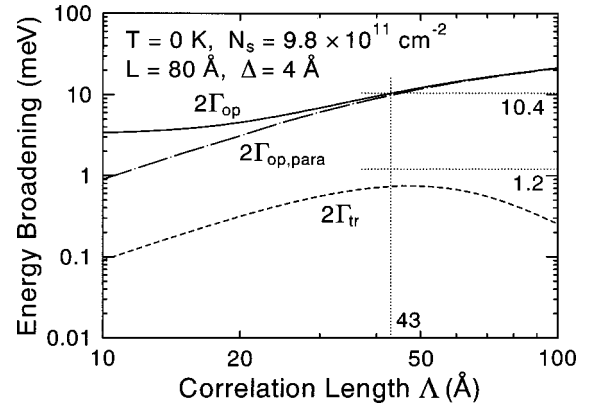


FIG. 2. Calculated  $2\Gamma_{\text{op}}$  and  $2\Gamma_{\text{tr}}$  due to interface roughness scattering, plotted as functions of  $\Lambda$ . The  $2\Gamma_{\text{op,para}}$  represents the linewidth without the nonparabolicity effect.

$$\frac{2\hbar}{\tau_{\text{tr}}(E)} = \frac{2m^* \Delta^2 \Lambda^2}{\hbar^2} F_{00}^2 \int_0^\pi d\theta \frac{1 - \cos \theta}{\epsilon(q, T)^2} e^{-q^2 \Lambda^2/4}. \quad (7)$$

Here,  $\epsilon(q, T)$  is the static dielectric function.<sup>7,9</sup>

It is useful here to compare the similar expressions for  $\Gamma_{\text{intra}}(E)$ ,  $\Gamma_{\text{inter}}(E)$ , and  $2\hbar/\tau_{\text{tr}}(E)$  in Eqs. (3)–(7). First, all the three are proportional to  $\Delta^2$ , and also to  $\Lambda^2$  for small  $\Lambda$ . Second,  $\Gamma_{\text{inter}}(E)$  is much smaller than  $\Gamma_{\text{intra}}(E)$ , because  $\tilde{q}$  is larger than  $q$  owing to  $E_{10}$ . Third,  $(1 - \cos \theta)/\epsilon(q, T)^2$  appearing only in  $2\hbar/\tau_{\text{tr}}(E)$  shows that forward scattering ( $\theta \sim 0$ ) makes no contribution to the transport energy broadening, and that screening reduces the scattering rate. Finally and most importantly, there are the factors  $(F_{00} - F_{11})^2$ ,  $F_{01}^2$ , and  $2F_{00}^2$  in front of the integrals. Since  $E_1$  is more sensitive to  $L$  than  $E_0$ ,  $F_{11}$  is much larger than  $F_{00}$ , which makes  $\Gamma_{\text{intra}}(E)$  much larger than  $2\hbar/\tau_{\text{tr}}(E)$ . (In the infinite barrier approximation,  $F_{11}$  is four times larger than  $F_{00}$ .)

At low temperatures, Eq. (7) with the substitution of Fermi energy  $E_F$  into  $E$  directly gives  $2\Gamma_{\text{tr}}$ . If the  $E$  dependence in Eqs. (3) and (4) and band nonparabolicity are negligible, the sum of Eqs. (3) and (4) is equal to  $2\Gamma_{\text{op}}$ .

In practice, however,  $2\Gamma_{\text{op}}$  is obtained by performing the integral in Eq. (1), where the nonparabolicity effect is to be introduced by replacing  $E_{10}$  with  $E_{10} - (1 - m_0^*/m_1^*)E$ . Here,  $m_0^*$  and  $m_1^*$  are the electron effective masses in the ground and first excited subbands, respectively, and are set at  $0.069m$  and  $0.076m$  according to the Kane model, where  $m$  is the free electron mass. In the numerical calculations,  $L = 80 \text{ \AA}$ ,  $N_s = 9.8 \times 10^{11} \text{ cm}^{-2}$ , and a barrier height of 1 eV were used. The other material parameters were taken from Table I in Ref. 7.

Figure 2 shows the calculation of  $2\Gamma_{\text{op}}$  (solid curve) in comparison with  $2\Gamma_{\text{tr}}$  (broken curve) as a function of  $\Lambda$  for  $\Delta = 4 \text{ \AA}$ . The dash-dotted curve shows  $2\Gamma_{\text{op,para}}$ , the linewidth without the nonparabolicity effect. It is shown that  $2\Gamma_{\text{op,para}}$  and  $2\Gamma_{\text{tr}}$  are proportional to  $\Lambda^2$  for small  $\Lambda$  with a difference in values of about an order of magnitude. For large  $\Lambda$ , the insensitivity of  $2\Gamma_{\text{tr}}$  to the forward scattering causes its value to be smaller. With nonparabolicity,  $2\Gamma_{\text{op}}$  has a lower limit of  $(1 - m_0^*/m_1^*)E_F = 3.3 \text{ meV}$  in addition to  $2\Gamma_{\text{op,para}}$ . As a result,  $2\Gamma_{\text{op}}$  is one order of magnitude larger than  $2\Gamma_{\text{tr}}$ , which explains the higher sensitivity of linewidth to interface roughness scattering.

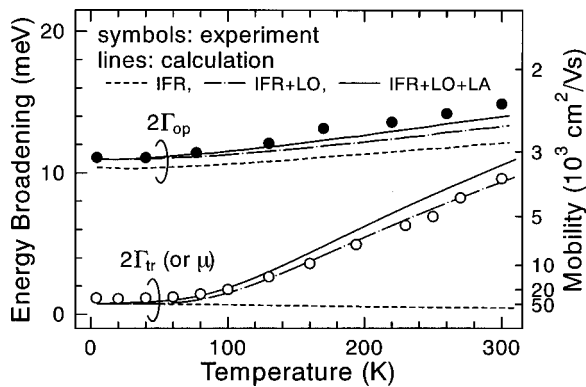


FIG. 3. Measured  $2\Gamma_{op}$  and  $2\Gamma_{tr}$  (or  $\mu$ ) are plotted as functions of temperature by solid and open circles, respectively. Calculated values with  $L = 80 \text{ \AA}$ ,  $N_s = 9.8 \times 10^{11} \text{ cm}^{-2}$ ,  $\Delta = 4 \text{ \AA}$ , and  $\Lambda = 43 \text{ \AA}$  are also plotted by lines. In the calculations, we considered interface roughness (IFR), LO phonon, and LA phonon scattering.

The value of 10.4 meV for  $2\Gamma_{op}$  without the contribution of phonon scattering, which will be shown below, agrees with the calculation for  $\Lambda = 43 \text{ \AA}$ . This is a reasonable value of  $\Lambda$  for the GaAs-on-AlAs interface.<sup>8</sup> The corresponding calculated value of  $2\Gamma_{tr}$  is 0.73 meV, which partly explains the experimental value of 1.2 meV. In the following, we use the pair of  $\Delta = 4 \text{ \AA}$  and  $\Lambda = 43 \text{ \AA}$  as representative; another pair in the range of  $\Delta = 3.5\text{--}5 \text{ \AA}$  and  $\Lambda = 55\text{--}30 \text{ \AA}$  is allowable.

Figure 3 shows the plots of the linewidth  $2\Gamma_{op}$  (solid circles) measured as a function of temperature. For comparison, the transport broadening  $2\Gamma_{tr}$ , or the mobility  $\mu$  (right vertical axis), is also plotted by open circles. At a low temperature ( $T = 4.5 \text{ K}$ ), as already seen in Fig. 1, the  $2\Gamma_{op}$  of 11.1 meV is much larger than the  $2\Gamma_{tr}$  of 1.2 meV. Note now that the linewidth  $2\Gamma_{op}$  slowly increases as the temperature increases up to 300 K, which is in contrast to the rapid increase of the transport broadening  $2\Gamma_{tr}$ .

To explain the experimental results, we also applied Ando's theory to LO phonon scattering and acoustic (LA) phonon scattering via deformation potential coupling. Since this theory is for elastic scattering processes, our analysis is a crude approximation for deriving the width of a zero-phonon band while ignoring phonon sidebands. The formulations we obtained are more complex; they will be presented elsewhere. With regard to transport, the formulations are the same as those in Ref. 7, except for a difference in wave functions.

The calculated results, obtained by including interface roughness (IFR), LO phonon, and LA phonon scattering, are also shown in Fig. 3 by broken (IFR), dash-dotted (IFR+LO), and solid (IFR+LO+LA) curves, respectively. Fine agreement between the experimental results and theoretical calculations was obtained by the solid curves for both linewidth and mobility.

At low temperatures, interface roughness scattering dominates absorption linewidth, though the intersubband LO

phonon emission process adds a little to the width. Even at room temperature, interface roughness scattering is still dominant, whereas the effects of LO and LA phonon scattering are small. This is because the difference in intrasubband scattering matrix elements for the two subbands is smaller in phonon scattering than in interface roughness scattering. In contrast, LO phonon scattering rapidly lowers electron mobility with increasing temperature, and the contribution of interface roughness scattering remains small, as is known very well. In this way, the same scattering mechanisms have very different influences on linewidth and mobility, which explains the apparent lack of correlation between the two.

It should be noted that the high sensitivity of linewidth to interface roughness scattering is due to the larger contribution of the first excited state than that of the ground state in Eq. (3), or  $F_{11} - F_{00} = \partial(E_1 - E_0)/\partial L$ . If one makes  $E_1 - E_0 = E_{10}$  insensitive to the change of  $L$  in double QWs or other structures, the dominant term  $\Gamma_{intra}(E)$  should vanish, and narrow linewidths should be obtained.

In summary, we have quantitatively studied the effects of interface roughness and phonon scattering on intersubband absorption linewidth in a GaAs/AlAs QW. We have obtained significant agreement between experimental data and theoretical calculations for both linewidth and mobility at temperatures ranging from 4.5 to 300 K. In this temperature range, interface roughness scattering is a very strong scattering mechanism for linewidth, because the contribution of the first excited subband is much larger than that of the ground subband. Phonon scattering processes have little influence on linewidth even at room temperature, while mobility is strongly affected by LO phonon scattering.

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