Response to "Comment on 'Electron mobility in modulation-doped heterostructures'"

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The high value of deformation potential $D=13.5$ eV proposed in the preceding Comment of Price is incorrect, since it contradicts low-temperature mobility data on high-purity GaAs crystals. We show that overestimation of the acoustic-mode scattering by Price results from incorrect analysis of the ionized-impurity scattering in modulation-doped heterostructures.

The preceding Comment of Price[1] is quantitatively incorrect. The proposed high value of GaAs deformation potential $D=13.5$ eV is not in agreement with the extensive low-temperature mobility data on high-purity crystals.[2,3] We show that overestimation of the acoustic-mode scattering by Price results from an analysis which incorrectly neglects the temperature dependence of ionized-impurity scattering in modulation-doped heterostructures (MDH). The analysis presented in the Comment after Mendez, Price, and Heiblum[4] involves an assumption that for MDH with electron density $N_s=1\times10^{11}$ to 6×10^{11} cm^{-2} ionized-impurity mobility is independent of temperature in the temperature range 4–40 K.

In order to illustrate that indeed there is a temperature dependence of ionized-impurity mobility, we consider the example of remote impurities. It can be shown that for a spacer width larger than 100 Å, the temperature dependence of remote impurity mobility μ_r can be written in the form[5]

$$\mu_r=\tfrac{5}{2}\mu_r^0\frac{(1-e^{-\alpha})^2}{\alpha^{5/2}}F_{3/2}(\eta)\ , \tag{1}$$

where $\alpha=\pi N_s\hbar^2/m^*kT$, $\eta=E_F/kT$ is the reduced Fermi energy, and $F_{3/2}(\eta)$ is the Fermi-Dirac integral of the order $\frac{3}{2}$. For highly degenerate electron gas, $\eta>>1$, $\alpha>>1$, and $\mu_r\simeq\mu_r^0$; i.e., it is independent of temperature. However, in the low density limit ($N_s\sim10^{11}$ cm^{-2}) $\eta\sim0$, $\alpha\sim1$, and the temperature dependence becomes significant.[6] In the temperature range 4–40 K, μ_r for $N_s=10^{11}$ cm^{-2} increases with temperature by as much as 60%. This change cannot be neglected in the analysis of the total electron mobility, since ionized-impurity scattering plays a dominant role in limiting the electron mobility in MHD with low electron gas density.[5,7]

The inaccuracy of the treatment discussed by Price[1] is apparent from Fig. 1. Here, $\alpha\equiv d(1/\mu)/dT$ is presented as a function of electron density. The results indicated with × were obtained by taking into consideration the temperature dependence of μ_r; i.e., $\alpha_{ac}=\alpha_{tot}-\alpha_r$. All other points represent results by the analysis of Mendez *et al.*[4] in which it is assumed that μ_r is temperature independent and that $\alpha_{ac}=\alpha_{tot}$. It is seen that for high values of N_s both approaches lead to similar results. However, for low values of N_s the analysis of Mendez *et al.*[4] underestimates α_{ac} by a factor of about 4. It is thus evident that the dependence of α_{ac} on electron density as discussed in the Comment[4] cannot be reliably used for determination of the deformation-potential value.

It must be pointed out that the $D=13.5$ eV used by Price is not in agreement with experimental electron mobility determined for very high-purity GaAs samples;[2,3] i.e., $\mu_e=200\,000$ cm^2/V s at 77 K. Taking $D=13.5$ eV the mobility limit at 77 K is only 130 000 cm^2/V s, i.e., significantly below experimental values. On the other hand, the mobility data on epitaxial GaAs crystals with negligible free-carrier screening effects were satisfactorily explained using $D=7$ eV in Ref. 2 and $D=8.6$ eV in Ref. 3. The value $D=7$ eV was also adopted by Walukiewicz, Ruda, Lagowski, and Gatos in Ref. 5 and by Lin, Tsui, Paalanen, and Gossard[6] and Lee, Shur, Drummond, and Morkoç.[8]

It should be pointed out that significantly greater values of the deformation potential were invoked in the analysis of electrical transport[9] and free-carrier adsorption[10] data obtained from bulk crystals of GaAs grown from the melt. In all melt-grown crystals there is an inherent large degree of electrical compensation which when not properly accounted for leads to an overestimation of the deformation-potential value.

The Comment by Price[1] also raises reservations concerning calculations of the optical-phonon scattering in MDH. Reservations (a) and (d), e.g., the three-dimensional approximation and the use of Matthiessen's rule, respectively, are applicable to the treatment of Walukiewicz *et al.*[5] These approximations, however, are more accurate than implied by the Comment. As discussed in Ref. 5, in the case of optical-phonon scattering, electron states in a wide energy range $3kT+\hbar\omega_0$ (i.e., $\gtrsim100$ meV at room temperature)

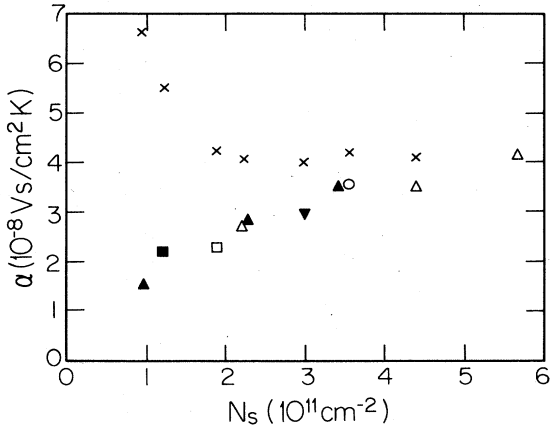

FIG. 1. Temperature coefficient α as a function of electron density. ×, results for α_{ac} obtained from analysis in this reply. All the other points represent results of analysis of Mendez *et al.* (Ref. 4) assuming temperature-independent ionized-impurity mobility.

participate in the scattering. The density of the initial and final states is therefore an average over few subbands. This corresponds to almost a constant distribution of the electron density within the well. Furthermore, experimental values of the room-temperature opitcal-phonon mobilities for MDH's in a wide electron density range (2×10^{11}–10^{12}) are within 8×10^3 to 9×10^3 cm^2/V s (Refs. 11 and 12) and are in good agreement with the three-dimensional optical-phonon mobility, i.e., ~ 8500 cm^2/V s.

We agree with the Comment that Matthiessen's rule can in general lead to errors in mobility calculations. These errors, however, are significant only when the dependence of the scattering processes on electron energy are very different. However, the dependence of acoustical- and optical-phonon scattering on energy is very similar, and thus Matthiessen's rule is a very good approximation. This reasoning is supported by the example considered by Price,[13] who found that an error of only 2.4% is introduced when Matthiessen's rule is applied to combine deformation-potential and piezoelectric acoustic phonon scattering.

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[7]There is an error in the value of acoustical-phonon mobility μ_{ac} in Fig. 3 of Ref. 5. The proper value, $\mu_{ac}\sim 4.5\times10^6$ cm^2/V s, can be found from Fig. 4 of Ref. 5. This new value of μ_{ac} affects the fitting parameter, i.e., the background impurity concentration changing its value from 1×10^{15} to 7×10^{14} cm^{-3}.

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