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Hot Electron Transport in Two-dimensional SiGe/Si Quantum Wells

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Abstract: ***The hot carrier energy loss rate in a two-dimensioal electron gas in SiGe/Si quantum well has been theoretically studied and carrier concentration ranging from 1.0x1012 to 5.0x1014 m-2. The energy loss rate in this highly non-parabolic system is dominated by acoustic deformation potential scattering, whereas the acoustic piezoelectric scattering is negligible. We also studied variation of energy loss rate with thickness of various quantum wells.***
Keywords: energy loss rate, acoustic deformation, acoustic piezoelectric, screening effect, SiGe, quantum well

I. INTRODUCTION

In general the two-dimensional (2D) system is now well understood. Low-dimensional semiconductors (LDS) structures have observed much attention due to their excellent importance and applications in Electronics and Device applications [1-5]. One of such important study is the electron-phonon interaction which explores the use of these LDS structures in high frequency ultrasonic generators and high frequency moderators as device applications. Under high electric field, the electron-phonon interaction in LDS structures play an important role in determining the transport properties viz, electron energy relaxation, mobility, phonon drag and diffusion thermopower, hall effect etc,. Due to the advanced crystal growth techniques and favorable energy gap in GaAs, GaInAs, GaSb, InSb structures, a lot more of experimental and theoretical studies have been carried out in literature over the last three to four decades in the above said transport properties. High power, high frequency and high temperature electronic devices usually requires group III nitride materials and are observed suitable for device applications [6]. Most devices are designed to operate under high electric field. At a high electric field, the electrons equilibrate at a much higher temperature than the lattice temperature. The determination of the temperature of electrons under electric field heating conditions in the steady sate provides useful information about electron-phonon interactions involved in the energy relaxation process. GaN has many applications in optoelectronic and electronic device technologies.

One might have anticipated that SiGe hole or electron systems would behave in a similar fashion to Si-MOSFETs because they are not expected to be piezoelectrically active. However, there are no data on electron systems, and previous thermopower work on a hole system was inconclusive [7, 8] in that the data were at relatively high temperatures (1.5-15 K) where it is difficult to distinguish the various hole-phonon (h-p) scattering mechanisms. The e-p (or h-p) interaction can also be probed by carrier energy loss. The energy loss rate depends on the carrier-phonon energy relaxation time, whereas phonon-drag thermopower reflects the carrier-phonon momentum relaxation time [9,10]. Thus the two types of measurement provide different but complementary ways to investigate carrier-phonon scattering. Previous measurements on the energy loss rates in SiGe electron systems are in accord with expectations. They agree with calculations assuming only screened deformation potential electron-phonon coupling [11, 12]

At low temperatures, the deformation potential scattering has a stronger temperature dependence, the precise form of which depends on the mechanism of electron-phonon scattering. Systems with screened, piezoelectric e-p scattering of the carriers, e.g., GaAs based structures, have been shown to give a T^4 dependence of drag [13] whereas those with only screened deformation-potential (DP) scattering show a T^6 dependence [14]. One might have anticipated that SiGe hole or electron systems would behave in a similar fashion to Si-MOSFETs because they are not expected to be piezoelectrically active. The electron-phonon interaction can also be probed by carrier energy loss. The energy loss rate depends on the carrier-phonon energy relaxation time, whereas phonon-drag thermopower reflects the carrier-phonon momentum relaxation time [15]. Thus the two types of measurement provide different but complementary ways to investigate carrier-phonon scattering. Previous measurements on the energy loss rates in SiGe electron systems are in accord with expectations. They agree with calculations assuming only screened deformation potential electron-phonon coupling [11, 12]. However, similar work on SiGe hole systems (where the 2D hole gas resided in a $Si_{1-x}Ge_x$ well) gave loss rates inconsistent with this mechanism. Early measurements were analyzed in terms of a screened, piezoelectric h-p coupling, but more recent work [16]

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Leaned towards unscreened deformation potential coupling (these two mechanisms are difficult to distinguish because both give the same power law dependence on T at low temperatures), with a small unscreened piezoelectric term contributing at temperatures < 0.5 K. The present thermopower measurements throw new light on this problem.

II. THEORETICL FORMULATION

The object of our investigation is a quantum well formed in SiGe/Si heterojunction. In our calculations, we assumed that electron transitions occur within the first size-quantization subband. In the one-phonon process, the momentum and energy conservation requirement prevents the more energetic acoustic phonons from scattering electrons. If and $\boldsymbol{q}$ and $\boldsymbol{q}'$ are the phonon wave vector in the short wavelength regions such that $\boldsymbol{Q} = \boldsymbol{q} + \boldsymbol{q}'$ is quite small so as to lie in the long wavelength region. Further, it will be assumed that the electrons are quasi-2D, with the electron wave function given by

$$\Psi_{\boldsymbol{k}}(\boldsymbol{r}) = \frac{1}{\sqrt{A}} e^{i\boldsymbol{k}*r} \Phi(z) \quad (1)$$

where A is the area in the plane of the layer, $\boldsymbol{k}$ and $\boldsymbol{r}$ are the usual two-dimensional vectors. Here only the first subband is assumed to be occupied.

It is convenient to calculate average energy loss per electron by calculating the energy gained by phonons from the electrons and dividing by the number of electrons (N_e) participate [17]

$$\langle P \rangle = -\frac{1}{N_e} \sum_{\boldsymbol{k},\boldsymbol{q},\boldsymbol{q}'} \hbar(w_{\boldsymbol{q}} + w_{\boldsymbol{q}'}) \frac{2\pi}{\hbar} \{(N_{\boldsymbol{q}} + 1)(N_{\boldsymbol{q}'} + 1) f(E_{\boldsymbol{k}'})[1 - f(E_{\boldsymbol{k}})] \quad (2)$$

$$- N_{\boldsymbol{q}} N_{\boldsymbol{q}'} f(E_{\boldsymbol{k}}) [1 - f(E_{\boldsymbol{k}'})]\} \; |M(\boldsymbol{q}, \boldsymbol{q}')|^2 \left|F(\boldsymbol{q}_z, \boldsymbol{q}_{z'})\right|^2 \delta(E_{\boldsymbol{k}'} - E_{\boldsymbol{k}} - \hbar(w_{\boldsymbol{q}} + w_{\boldsymbol{q}'}))$$

with $f(E_{\boldsymbol{k}})$ and $N_{\boldsymbol{q}}$ respectively representing the Fermi distribution with T_e and Bose distribution with T_L. $\left|F(\boldsymbol{q}_z, \boldsymbol{q}_{z'})\right|^2$ is the overlap integral.

Following the subband procedure and assuming the phonon modes to be the same as those of bulk semiconductors, one can calculate the expression for the energy loss rate for screened acoustic deformation potential, piezoelectric scattering for the average electron energy loss rate due to screened acoustic deformation potential scattering can be expressed as

$$\langle P \rangle_{DP} = \frac{E_d^2 m^* k_F}{4N_s \pi^2 \rho \hbar} \int_0^\infty \int_0^\infty q^2 S^2(q_\parallel) F_1(\boldsymbol{q}) \gamma(\eta_-, \eta_+) dq_\parallel dq_z \quad (3)$$

where $F_1(\boldsymbol{q}) = |F(q_z)|^2 \left[exp\left\{\frac{\hbar\omega_{\boldsymbol{q}}}{k_B}\left(\frac{1}{T_L} - \frac{1}{T_e}\right)\right\} - 1\right] N_{\boldsymbol{q}}$

and $\gamma(\eta_-, \eta_+) = \int_0^\infty \frac{1}{\sqrt{X}} f(X + \eta_-^2)\left[1 + f(X + \eta_+^2 - \mu)\right] dX$

where $f\left(X + \eta_\pm^2\right) = \frac{1}{[exp\{\xi(X+\eta_\pm^2)\}+1]}$

with $\eta_\pm^2 = \left(\frac{q_\parallel}{2k_F} \pm \frac{m^* \omega_{\boldsymbol{q}}}{\hbar k_F q_\parallel}\right)^2$, and $\xi = \frac{E_F}{k_B T_e}$ and $\mu = \frac{E_f}{E_F}$ with $E_f = k_B T_e \ln\left[\exp\left(\frac{E_F}{k_B T_e}\right) - 1\right]$, where Fermi energy, $E_F = \left(\frac{\pi\hbar^2 N_s}{m^*}\right)$

The screening function, $S^2(q_\parallel) = \left[1 + \frac{q_s}{q_\parallel} H(q_\parallel)\right]^{-2}$ with screening parameter, $q_s = \left(\frac{2m^* e^2}{\varepsilon_s \hbar^2}\right)$.

The screening form factor, $H(q_\parallel) = \frac{b\,(8b^2 + 9bq_\parallel + 3q^2)}{8(b + q_\parallel)^3}$ for heterojunction and

$H(q_\parallel) = \frac{4}{4\pi^2 + L^2 q_\parallel^2}\left[\frac{3}{4} L q_\parallel + \frac{2\pi^2}{L q_\parallel} - \frac{8\pi^4 (1 - e^{-L q_\parallel})}{L^2 q_\parallel^2 (4\pi^2 + L^2 q_\parallel^2)}\right]$ for Quantum Wells.

Similarly, the average electron energy loss rate for screened acoustic piezoelectric scattering

$$\langle P \rangle_{PZ} = \frac{(eh_{14})^2 m^* k_F}{4N_s \pi^2 \rho \hbar} \int_0^\infty \int_0^\infty A_i S^2(q_\parallel) F_1(\boldsymbol{q}) \gamma(\eta_-, \eta_+) dq_\parallel dq_z \quad (4)$$

where A_i for longitudinal piezoelectric scattering is given by $A_l = \left(\frac{9 q_\parallel{}^4 q_z^2}{2\boldsymbol{q}^6}\right)$ and for transverse piezoelectric scattering $A_t = \left(\frac{8 q_\parallel{}^2 q_z^4 + q_\parallel{}^6}{2\boldsymbol{q}^6}\right)$. h_{14} is the piezoelectric coupling constant.

III. RESULTS AND DISCUSSION

Theoretical calculations of power loss per electron P as a function of electron temperature for acoustic deformation potential and acoustic piezoelectric scattering processes have been performed for the SiGe/Si quantum well heterostructure. The material parameters used in calculations characteristic of SiGe are $m^* = 0.92 m_0$, V_s =8.433x10^3 m/s, ρ = 2329 kg/m^3 and ε_s = 11.7.

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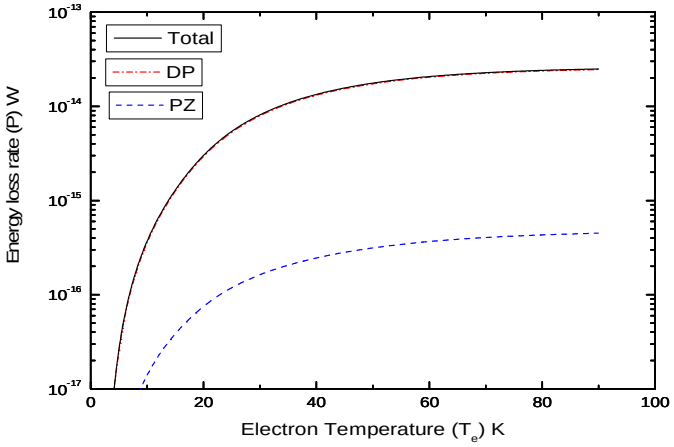


Figure 1: Electron energy loss rate as a function of electron temperature. The blue dashed line represents contribution due to piezoelectric scattering, red dash-dot line for deformation potential scattering and black continuous line for total contribution from both scattering mechanisms.

In figure 1, the contributions to energy loss rate from acoustic deformation potential ad acoustic piezoelectric scattering mechanisms are shown. In calculations we used carrier concentration N_s = 1.0x10^{13} m^{-2}, quantum well width L = 50 A^0, lattice temperature T_L = 3.0K deformation potential constant E_d = 12.0 eV and h_{14} = 0.6x10^9 V/m. In the temperature region we considered here indicates that acoustic deformation potential scattering mechanism is dominant mechanism compared to piezoelectric scattering mechanism. The same dominant mechanism was also observed in 2D GaAs, GaN, GaInAs quantum wells [17-19]. In the acoustic deformation potential scattering mechanism, the only adjustable parameter is the deformation potential constant E_d. When the experimental observations are available for this SiGe quantum wells, this theoretical calculations will show good agreement with the observations. In the figure 1, the blue dashed line shows the energy loss rate of theoretical data for piezoelectric scattering, red dashed-dot line shows for acoustic deformation potential scattering and black continuous line for the total contribution from both scattering. It is clear that, the piezoelectric scattering is completely negligible for this SiGe heterostructure. Therefore the dominant scattering mechanism is due to the acoustic deformation potential. In both the scattering mechanisms, we incorporated dynamical screening effect. The inclusion of dynamical screening effect reduces the energy loss rate an order of magnitude [17,18].

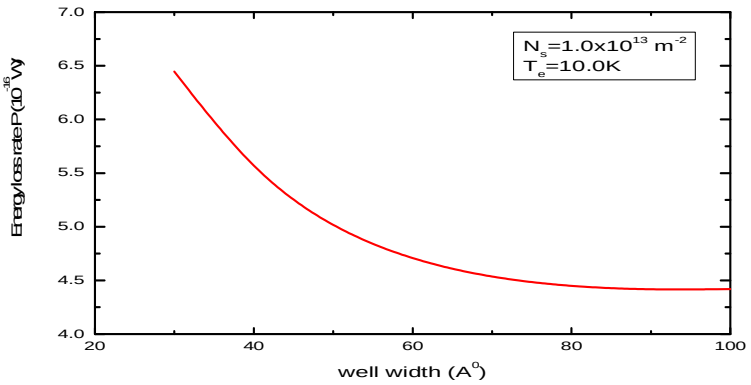


Figure 2: The variation of electron energy loss rate with quantum well width.

Figure 2 shows the variation of energy loss rate with quantum well width in the acoustic deformation potential scattering with a deformation potential constant E_d= 12.0 eV, at T_e=10.0K and carrier concentration N_s=1.0x10^{13}m^{-2}. It is observed that, energy loss rate decreases with increase in well width. The same behavior was also observed in GaAs [20], GaN, GaInAs quantum wells. Our calculations in figure 2 show a very similar trend for 2D GaAs quantum wells.

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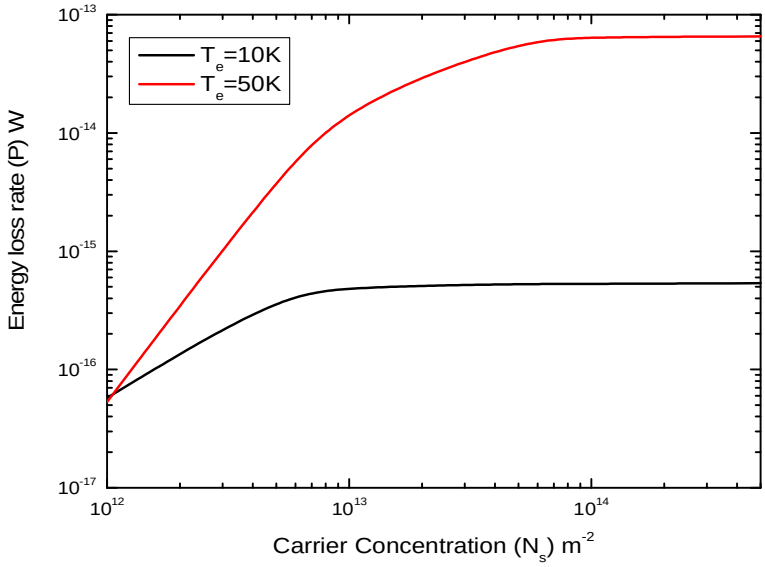


Figure 3: The variation of electron energy loss rate with carrier concentration for different carrier temperatures.

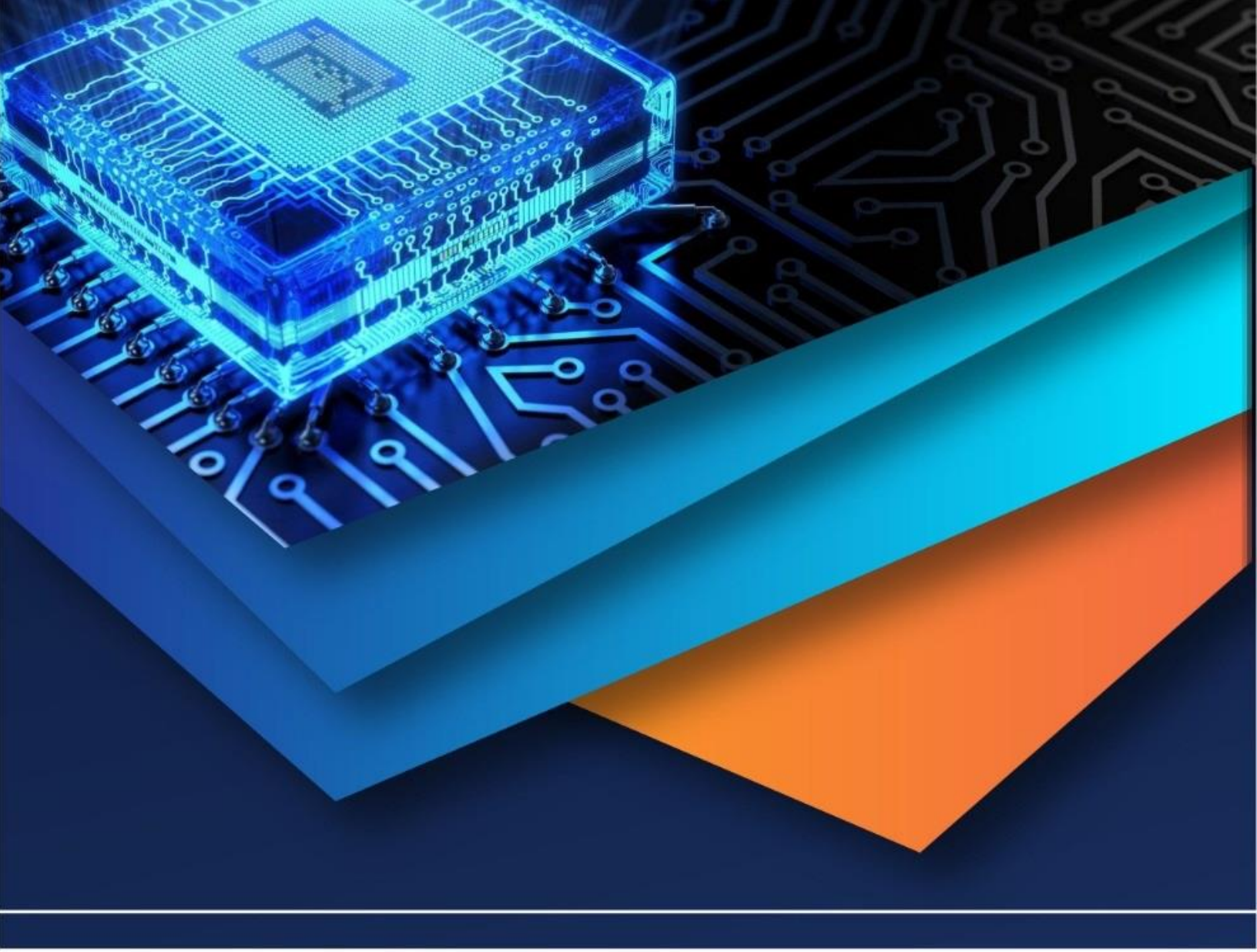
The dependence of Electron energy loss rate with Carrier concentration is shown in figure 3. The noticeable point is that, energy loss rate became almost saturation when the carrier concentration reaches greater than $1.0x10^{13}$ m^{-2}. Also observed that, as carrier temperature increases there is an increase in energy loss rate. This is in agreement with other material heterostructures.

IV. CONCLUSIONS

The dependence of energy loss rate in SiGe/Si quantum well through acoustic deformation potential and acoustic piezoelectric scattering on the carrier temperature were calculated. The dynamical screening of the electron-phonon interaction was taken into account. Consideration of the dynamical screening effect will reduce the energy loss rate considerably. Acoustic deformation potential scattering is the dominant scattering mechanism at low temperature as compared to acoustic piezoelectric scattering was observed in this SiGe heterostructure same as that of other GaAs, GaN, GaAlAs heterostructures.

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