Surface Acoustic Waves probe of the $p$-type Si/SiGe heterostructures

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The surface acoustic wave (SAWs) attenuation coefficient $\Gamma$ and the velocity change $\Delta V/V$ were measured for $p$-type Si/SiGe heterostructures in the temperature range 0.7 - 1.6 K as a function of external magnetic field $H$ up to 7 T and in the frequency range 30-300 MHz in the hole Si/SiGe heterostructures. Oscillations of $\Gamma$ (H) and $\Delta V/V$ (H) in a magnetic field were observed. Both real $\sigma_1$ (H) and imaginary $\sigma_2$ (H) components of the high-frequency conductivity have been determined. Analysis of the $\sigma_1$ to $\sigma_2$ ratio allows the carrier localization to be followed as a function of temperature and magnetic field. At $T=0.7$ K the variation of $\Gamma$, $\Delta V/V$ and $\sigma_1$ with SAW intensity have been studied and could be attributed to 2DHG heating by the SAW electric field. The energy relaxation time is found to be dominated by scattering at the deformation potential of the acoustic phonons with weak screening.

I. INTRODUCTION

For the first time an acoustic method has been applied in a study of $p$-type Si/SiGe heterostructures. Since Ge and Si are not piezoelectrics the only way to measure acoustoelectric effects in these systems is a hybrid method: a SAW propagates along the surface of a piezoelectric LiNbO$_3$ while the Si/SiGe sample is being slightly pressed onto LiNbO$_3$ surface by means of a spring. In this case a strain from the SAW is not transmitted to the sample and it is only the electric field accompanying the SAW that penetrates into the sample and creates currents that, in turn, produce a feedback to the SAW. As a result, both SAW attenuation $\Gamma$ and velocity $V$ appear to depend on the properties of the 2DHG. SAW-acoustics proves to be an effective probe of heterostructure parameters, especially as it is contactless and does not require the Hall-bar configuration of a sample. Moreover, simultaneous measurements of attenuation and velocity of SAW provide a unique possibility to determine the complex AC conductivity, $\sigma_{xx}(\omega) = \sigma_1(\omega) - i\sigma_2(\omega)$, as a function of magnetic field $H$ and SAW frequency $\omega$. Furthermore, the magnetic field dependence of $\sigma_{xx}(\omega)$ provides information on both the extended and localized states.

II. EXPERIMENTAL RESULTS

The absorption $\Gamma$ and velocity shift $\Delta V/V$ of the SAW, that interacts with 2DHG in the SiGe channel, have been measured at temperatures $T=0.7-1.6$ K in magnetic fields up to $H=7$ T. DC-measurements of the resistivity components $\rho_{xx}$ and $\rho_{xy}$ have also been carried out in magnetic fields up to 11T in the temperature range 0.3-1.3 K and have shown the integer quantum Hall effect.

The samples were modulation doped Si/SiGe heterostructures with 2DHG sheet density $p = 2 \times 10^{11}$ cm$^{-2}$ and mobility $\mu = 10500$ cm$^2$/Vs.

High frequency conductivity $\sigma_{xx}^{AC} = \sigma_1 - i\sigma_2$ is extracted from simultaneous measurements of $\Gamma$ and $\Delta V/V$, using eqs. 1-5 of the literature.

It turns out, that at $T=0.7$ K and filling factor $\nu=2$ ($H = 4.3$ T) $\sigma_1 \simeq \sigma_2$ (fig.2). At the same time $\sigma_1 \gg \sigma_{dc}^{AC}$. These facts suggest that only some of holes in the 2D-channel are localized, and $\sigma_{xx}^{AC}$ is determined by both localized and delocalized holes. For total localization one needs $\sigma_1 \ll \sigma_2$, $\sigma_{dc}^{AC}=0$. At $\nu=3$ ($H=2.9$ T) localization effects are negligible: $\sigma_1 \simeq \sigma_{dc}^{AC} \gg \sigma_2$.

At $T=0.7$ K we have measured the dependences of $\Gamma(H)$, $\Delta V/V(H)$ and $\sigma_1(H)$ on the SAW intensity at...
30MHz. Fig. 3a shows $\sigma_1$ versus $P$ (the RF-source power) for magnetic fields of $H = 2.9\text{T}$ and $4.3\text{T}$. Fig.3b illustrates the temperature dependence of $\sigma_1$ measured in the linear regime. One can see from these plots that $\sigma_1$ increases with increasing temperature and SAW power.

For delocalized holes in this magnetic field, the observed nonlinear effects (Fig.3a) are probably associated with carrier heating. One may describe 2DHG heating by means of a carrier temperature $T_c$, greater than the lattice temperature $T$, provided that the following condition is met:

$$\tau_0 << \tau_{cc} << \tau_c. \tag{1}$$

Here $\tau_0$, $\tau_{cc}$ and $\tau_c$ are the momentum relaxation time, the carrier-carrier interaction time and the energy relaxation time, respectively. Calculations give $\tau_0 = 1.4 \times 10^{-12}\text{s}$; $\tau_{cc} = 6.4 \times 10^{-11}\text{s}$; $\tau_c$ will be discussed below.

The carrier temperature $T_c$ is determined using SdH thermometry by comparing the dependences $\sigma_1(T)$ and $\sigma_1(T)$. To characterize heating process one needs to extract the absolute energy losses as a result of the SAW interaction with the carriers $Q = \sigma_{xx} E^2 = 4GW$, where $W$ is the input SAW power scaled to the width of the sound track, $E$ is the intensity of the SAW electric field:

$$|E|^2 = K^2 \frac{32\pi}{V} (\varepsilon_1 + \varepsilon_0) \frac{z(q) q e^{-2qa}}{1 + \left( \frac{m_{ac}}{\varepsilon_0 q^2} t(q) \right)^2} W. \tag{2}$$

$K^2$ is the electromechanical coupling constant of the lithium niobate (Y-cut), $q$ is the SAW wave vector; $\varepsilon_s$, $\varepsilon_0$ and $\varepsilon_1$ are the dielectric constants of semiconductor, free space and LiNbO$_3$, respectively; $a$ is the width of the sample-LiNbO$_3$ clearance; $z(q)$ and $t(q)$ are functions to allow for the electrical and geometrical properties of the sample.

We have analyzed the energy losses rate per hole $Q = \dot{Q}/p$ as a function of $T_c$ (Fig.4). In the inset, $Q$ is plotted versus $(T_c^5 - T^5)$ and a linear dependence is illustrated.

$$A_5 = \frac{3\sqrt{2}m^2(5)D^2 k_B^3}{\pi^{3/2} s^2 h^3 p^{1/2} \rho}, \tag{3}$$

where $\rho$ is the mass density, $s$ is the longitudinal sound velocity, $m=0.24m_e$ is the effective mass. Thus, one
can determine the value of the deformation potential as $D_{ac} = 5.3 \pm 0.3$ eV. The value of $D_{ac}$ calculated from DC measurements of phonon-drag thermopower was reported to be $5.5 \pm 0.5$ eV for the same 2DHG Si/SiGe sample.

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1 I.L. Drichko, A.M. Diakonov, I.Yu. Smirnov, Y.M. Galperin, and A. I. Toropov, *Phys.Rev.B* **62**, 7470 (2000).
2 T.E. Whall, N.L. Mattey, A.D. Plews, P.J. Phillips, O.A. Mironov, R.J. Nicholas and M. J. Kearney, *Appl. Phys. Lett.* **64**, 357 (1994).
3 A.L. Efros, *ZETF* **89**, 1834 (1985) [*JETP* **89**, 1057 (1985)].
4 G. Ansaripour, G. Braithwaite, M. Myronov, O.A. Mironov, E.H.C. Parker and T.E. Whall, *Appl. Phys. Lett.* **76**, 1140 (2000).
5 Yu.F. Komnik, V.V. Andrievskii, I.B. Berkutov, S.S. Kryachko, M. Myronov and T.E. Whall, *Low Temp. Phys.* **26**, 699 (2000) [*Fiz. Nizk. Temp.* **26**, 829 (2000)].
6 I.L. Drichko, A.M. Diakonov, V.D. Kagan, A.M. Kreshchuk, T.A. Polyanskaya, I.G. Savel’ev, I.Yu. Smirnov and A.V. Suslov. *FTP* **31**, 1357 (1997) [*Semiconductors* **31**, 1170 (1997)].
7 V. Karpus, *FTP* **20**, 12 (1986) [*Sov. Phys. Semicond.* **20**, 6 (1986)].
8 S. Agan, O.A. Mironov, M. Tsaioudou, T.E. Whall, E.H.C. Parker, P.N. Butcher, *Microelectronic Engineering* **51-52**, 527 (2000).