Study of overheating effects in SiGe-based p-type heterostructures: Methods of the hole temperature determination

Untersuchung von Überhitzungseffekten in p-Typ SiGe-Heterostrukturen: Methoden zur Bestimmung der Temperatur der Leitungslöcher

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The effect of charge carrier overheating is studied in the p-type $Si/Si_{0.87}Ge_{0.13}/Si$ heterostructure. The hole temperature T_h can be calculated using three different methods: From a comparison of the changes in the amplitude of the Shubnikov-de Haas oscillations under the influences of temperature and current, from a comparison of the change of phase relaxation time in the weak localization effect obtained at different temperatures and minimum current and at a given temperature but at different values of current, and from a comparison of the temperature and current dependence of the sample resistance. The temperature dependences values of T_h obtained using three different methods were identical and exhibit transition of the two-dimensional system under study from the regime of "partial inelasticity" to that of small angle scattering at temperature lowering.

Keywords: quantum well / electron overheating effect / electron-phonon relaxation time

Die Überhitzung der Ladungsträger wurde in p-Typ Si/Si 0.87 Ge 0.13/Si Heterostrukturen untersucht. Die Lochtemperatur T_h kann mit drei unterschiedlichen Methoden berechnet werden: Durch den Vergleich der Amplitudenänderungen der Shubnikov-de Haas Oszillationen unter den Einflüssen von Temperatur und Stromstärke, durch den Vergleich der Änderung der Phasenrelaxationszeit im schwachen Lokalisierungseffekt bei unterschiedlichen Temperaturen, minimaler Stromstärke und bei gegebener Temperatur und unterschiedlicher Stromstärke, sowie durch den Vergleich die Abhängigkeit des Probenwiderstandes von Temperatur- und Stromstärke. Die Werte der Temperaturabhängigkeit von T_h, die nach drei verschiedenen Methoden erhalten wurden, waren identisch und zeigten einen Übergang des betrachteten zweidimensionalen Systems vom Bereich der "partiellen Inelastizität" zur Kleinwinkelstreuung bei tieferer Temperatur.

Schlüsselwörter: Quantenmulde / Elektronenüberhitzungseffekt / Elektron-Phonon-Relaxationszeit

1 Introduction

Many studies have been devoted to the investigation of the collective excitations in low-dimensional semiconductor systems. The very rapid development of nanotechnologies makes it possible to improve continuously the quality of such systems, in particular its conductivity. The electron-phonon scattering is a one of the most important factors, which have a large influence on the conductivity. Electron-phonon interaction leads, apart from the scattering processes, to a mutual influence of a nonequilibrium state of the electron and phonon subsystems caused either by an electric field or temperature gradient. The so-called electron overheating effect arises when power is directly dissipated in the electron subsystem leading to an overheating of the electrons with respect to that of phonons. As a result, the electron temperature T_e exceeds the phonon temperature T_{ph} under the acting of a warming electric field (current) or of other "heating" factors. The electron overheating effect plays an important role in several applications, such as the dc superconducting quantum interference device (dc SQUID), where it sets an upper limit to the energy resolution [1], or the normal metal hot-electron bolometer

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(NHEB), where the electron gas is used as thermal sensing element [2] and so on. The aim of this work is to investigate the hole-phonon interaction in 2D hole gas in $Si/Si_{0.87}Ge_{0.13}/Si$ heterostructure and, in particular, to obtain information about the time and the temperature dependencies of the hole-phonon interaction.

The transfer of excess energy from the electron (hole) to the phonon system, even in condition of strong elastic scattering, is governed by the time τ_{eph}. Information about the charge carrier interaction with phonons at low temperatures (~1 K) cannot be obtained from the behavior of the quantum corrections to the conductivity due to the weak localization and charge carrier interaction effects [3, 4], since at such temperatures the dominant inelastic relaxation process is charge carrier scattering. The value τ_{eph} can be calculated from the data for the electron overheating effect with the use of the heat balance equation, which assumes that in the stationary condition the electrical power $P = E^2\sigma$ released in a unit volume is equalized by the amount of energy transferred by the electrons (hole) to the lattice per unit time:

$$E^2\sigma = \int_{T_{ph}}^{T_e} \frac{C_e(T)dT}{\tau_{eph}(T_{eph})}. \qquad (1)$$

Here $C_e(T) = \gamma T$ is electronic heat capacity. In the steady state $\tau_{eph}(T)$ in Eq. (1) corresponds to a certain temperature T_{eph} that characterizes the charge carrier interaction with phonon under conditions of electron (hole) overheating. Then the Eq. (1) can be rewritten as [5]

$$T_e - T_{ph} = \frac{E^2\sigma}{\gamma T_{eph}} \tau_{eph}(T_{eph}). \qquad (2)$$

Since the value of γ is unknown for the system under studying for $T_{eph} = (T_e + T_{ph})/2$ Eq. (2) implies the following relation given by Ref. [6]:

$$(kT_e)^2 = (kT_{ph})^2 + \frac{6}{\pi^2}(eE)^2 D\tau_{eph}. \qquad (3)$$

where D is the charge carrier diffusion coefficient, and E is the electric field that leads to heating of the electrons (holes). This relation is obtained from Eq. (2) with the electronic heat capacity and conductivity expressed in terms of the density of states ν_{ds}: $C_e = (\pi^2/3)k^2\nu_{ds}T$ and $\sigma = e^2\nu_{ds}D$. For 2D gas of charge carriers $\nu_{ds} = m^*/(\pi\hbar^2)$, $D = (1/2)\upsilon_F^2\tau$, and the Fermi velocity $\upsilon_F = (\hbar/m^*)(2\pi n)^{1/2}$. The elastic scattering time τ can be determined from the formula $\rho^{-1} = ne^2\tau/m^*$, where m^* is effective mass. The electric field in a conducting channel of length L and width a can be found from the values of the current I and the resistance per square ρ: $E = IR/L = I\rho/a$ (since $R = \rho L/a$). The convenience of Eq. (3) is supported by the fact that 2D system is characterized only by value D. For T_{ph} one should take the temperature of the crystal. Experimentally, this problem is reduced to the estimate of the electron (hole) temperature T_e, which changes under the influence of a large enough current. In the present study the overheating effect of charge carriers was realized in p-type heterostructures with a $Si_{0.87}Ge_{0.13}$ quantum well. The temperature of the overheated holes T_h was calculated using three different methods: One of them consists is comparison of the change in the amplitude of the Shubnikov-de Haas oscillations (SdHO) under the influences of current and under the influence of temperature. The second method compares the phase relaxation time in the effect of weak localization (WL) obtained at different temperatures and minimum current and at a certain temperature but at different values of current. The third method based comparison of the temperature and current dependencies of the sample resistance.

2 Sample preparation

The Si < B > $/Si/Si_{0.87}Ge_{0.13}/Si$ heterostructure was grown by molecular beam epitaxy (MBE) at WarwickUniversity [7]. The procedure of the sample growth was as follows: The SiGe strained layers were grown on n^- Si (001) substrates at a growth rate 0.1 nm/s by solid source molecular beam epitaxy, in a V G V90S system. Prior to growth the wafers were chemically cleaned in a modified RCA etch, followed by a 90 s 5% HF dip to hydrogen terminate the surface. The last cleaning stage consisted of an *in situ* 860 °C flash off to remove any residual native oxide, followed by growth of a 250 nm high quality Si buffer. The temperature was reduced to 450 °C during this process before growing the $Si_{0.87}Ge_{0.13}$ 10 nm thick quantum well and 25 nm thick Si spacer layer. Growth was then interrupted for the *in situ* 30 min anneal at temperature in the range 450–800 °C. Finally, in remote doped structures a 50 nm Si-B doping supply layer with boron concentration 2.5×10^{18} cm^{-3} was grown at 600 °C. The doping layer was deposited after the annealing to minimize any temperature dependent B diffusion into the $Si_{0.87}Ge_{0.13}$ channel.

Specimens were structurally characterized by cross sectional and plan view transmission electron microscopy using a JEOL JEM-2000fx transmission electron microscope (TEM) operating at an accelerating voltage of 200 keV and high resolution secondary ion mass spectroscopy Atomika 4500 (HRSIMS) using 500 and 250 eV O_2^+ sources at normal incidence. Positron annihilation spectroscopy (PAS) was also used to examine open-volume defects such as vacancies [7]. High resolution x-ray diffraction PanalyticalX'Pert Pro MRD (HRXD) was used to determine the Ge concentration and strain condition.

The lowest temperature of the measurements was 337 mK. At low temperature the Hall concentration of holes in this structure was $\rho_H = 1.9 \times 10^{11}$ cm^{-2},the mobility was $\mu = 12700$ cm^2/Vs.

3 Experimental results and discussion

The dependencies $\rho_{xx}(B)$ and $\rho_{xy}(B)$ measured at the lowest temperatures are illustrated in *Fig. 1.* The curves at low magnetic fields (<0.2 T) exhibit the negative magnetoresistance and pronounced SdHO at higher magnetic fields (>0.5 T).

To estimate the hole-phonon energy relaxation time the hot-hole temperature was measured in three different ways. In the first method [8], the hole temperature T_h was found by comparing the SdHO amplitude change with current and with temperature as it shown in *Fig. 2.* The amplitude variation in these two cases were analyzed for three extrema (with filling factors $\nu = 8$, 10, and 12) in the magnetic field region 0.8–3.5 T. The quantum numbers are found from the off-diagonal component of the resis-

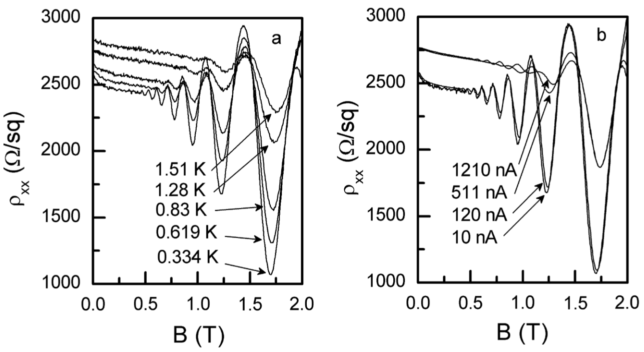

Figure 1. Change of the sample magnetoresistance at various temperatures (a) and at various currents (b).

Bild 1. Änderung des Magnetwiderstandes bei unterschiedlichen Temperaturen (a) und unterschiedlichen Stromstärken (b).

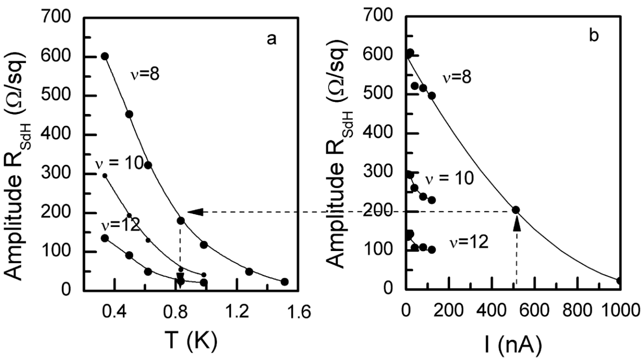

Figure 2. Change in the amplitude of the SdHO with quantum numbers upon changes in temperature (a) and current (b).

Bild 2. Änderung in der SdHO-Amplitude mit den Quantenzahlen bei der Änderung von Temperatur (a) und Stromstärke (b).

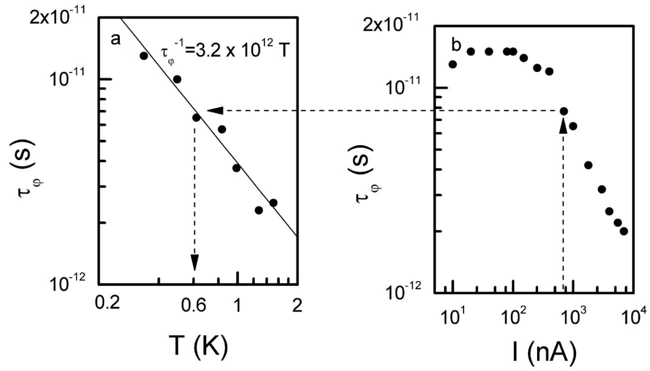

Figure 3. Temperature (a) and current (b) dependencies of the phase relaxation time τ_φ.

Bild 3. Temperatur- (a) und Stromstärkenabhängigkeit (b) der Phasenrelaxationszeit τ_φ.

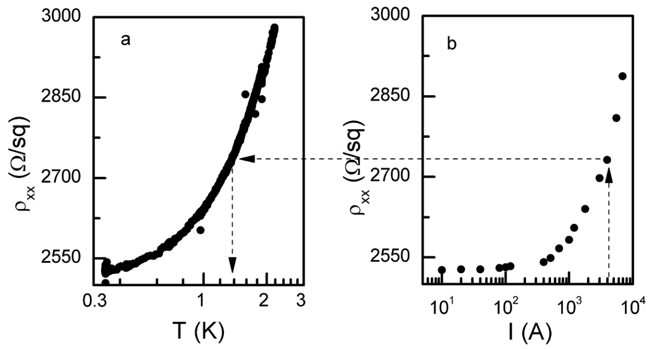

Figure 4. Temperature (a) and current (b) dependencies of the sample resistance.

Bild 4. Temperatur (a) und Stromstärkenabhängigkeit (b) des Probenwiderstandes.

tivity $\rho_{xy}(B)$ using the equation for resistance quantization under the condition of the quantum Hall effect $h/e\nu$.

The second method is based on the fact that the initial parts of the curves of the sample resistance vs. magnetic field demonstrate a negative magnetoresistance effect, Fig. 1a and 1b, which falls off noticeably in amplitude as the temperature is raised. This is just how the quantum correction to the resistance from the WL effect behaves in the case of weak spin-orbit scattering [9]. The WL correction to the conductivity in 2D case in perpendicular magntic field can be described by formula [10]:

$$\Delta\sigma^{WL}(B) = \frac{e^2}{2\pi^2\hbar}\left[\frac{3}{2}\cdot f_2\left(\frac{4eBD\tau_\varphi^*}{\hbar}\right) - \frac{1}{2}\cdot f_2\left(\frac{4eBD\tau_\varphi}{\hbar}\right)\right] \qquad (4)$$

where $f_2(x) = \ln x + \Psi(1/2 + 1/x)$, Ψ is the logarithmic derivative of the Γ-function; $\left(\tau_\varphi^*\right)^{-1} = \tau_\varphi^{-1} + (4/3)\tau_{so}^{-1}$, τ_φ and τ_{so} are times of phase and spin-orbit relaxation respectively. To go from the measured values of the resistance to the quantum corrections to the conductivity one can use the relation $-\Delta\sigma_{xx} = \dfrac{\rho_{xx}(B) - \rho_{xx}^0(0)}{\rho_{xx}(B)\rho_{xx}^0}$. The values of τ_φ and τ_{so} were used as fitting parameters for a numerical adjusting of the experimental data by Eq. (4). As a result of the calculations rather good description of the experimental data was achieved and we obtained the temperature dependence of the electron dephasing time $\tau_\varphi(T)$ (symbols on *Fig. 3*a) that can be approximated by a power-law function $\tau_\varphi^{-1}(T) = 3.2 \times 10^{-12}\, T$ (solid line on Fig. 3a) which is typical for a charge carrier interaction in a 2D system [11]. The same calculations were made to get values $\tau_\varphi(E)$ (symbols in Fig. 3b).

The temperature variation of the resistance of the sample in zero magnetic fields (*Fig. 4*a) also confirms the assumption that one observes the WL: the minimum and the increase of the resistance with decreasing temperature are due to the contribution of quantum corrections to the conductivity, which grows as the temperature is lowered. This feature gives a possibility to calculate T_h by direct comparison between temperature and current dependencies of the sample resistance.

The temperature dependencies of the hole-phonon relaxation time found using all three methods are shown in *Fig. 5*.It is important to note that the temperature dependence of the hole-phonon relaxation time $\tau_{hph}(T_{hph})$ is identical for all tree methods used. The experimental points fall on the same curve, which suggests that the $\tau_{hph}(T_{hph})$ value is independent of the magnetic field and that all three methods of the hole temperature calculations are equivalent. A common trend of $\tau_{hph} = 9 \times 10^{-9}\ T^{-2}$ s (dash line at Fig. 5) is seen, which changes to $\tau_{hph} \propto\ T^{-5}$ (dotted line in Fig. 5) at $T \sim 0.4$ K for all three curves. These dependen-

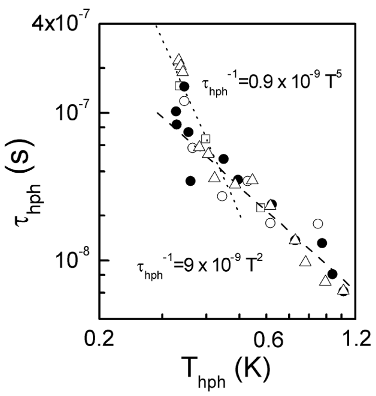

Figure 5. Temperature dependence of hole-phonon relaxation times determined by the change in the amplitude of the SdHO for quantum numbers ν = 8 (□) and 10 (○); using temperature and current dependencies of the phase relaxation time (●); using temperature and current dependencies of the sample resistance (△).

Bild 5. Temperaturabhängigkeit der Löcher-Phononenrelaxationszeiten, bestimmt durch die Änderungen der Amplitude der SdHO für die Quantenzahlen ν= 8 (□) und 10 (○), durch die Temperatur- und Stromstärkeabhängigkeit der Phasenrelaxationszeit (●), und durch die Temperatur- und Stromstärkeabhängigkeit des Probenwiderstandes (△).

cies agree with the theoretical predictions for 2D electron systems and describe processes with ‚partial inelasticity' and small angle scattering [12] at temperature lowering.

4 Conclusion

The effect of charge-carrier overheating in a two-dimensional hole gas is realized in a Si < B > /Si/$Si_{0.87}Ge_{0.13}$/Si quantum well. The Shubnikov-de Haas oscillation amplitude, the hole phase relaxation time, and temperature and current dependencies of resistance are used as a "thermometer" to measure the temperature of overheated holes. The temperature dependencies of the hole-phonon relaxation time found using all three methods are identical. The analysis of the temperature dependence of the hole-phonon relaxation time reveals a transition of the 2D system from the regime of "partial inelasticity" to that of small-angle scattering.

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