Quantum Hall Effect induced by electron-electron interaction in disordered GaAs layers with 3D spectrum

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Abstract

It is shown that the observed Quantum Hall Effect in epitaxial layers of heavily doped n-type GaAs with thickness $(50-140$ nm) larger the mean free path of the conduction electrons $(15-30$ nm) and, therefore, with a three-dimensional single-particle spectrum is induced by the electron-electron interaction. The Hall resistance R_{xy} of the thinnest sample reveals a wide plateau at small activation energy $E_a = 0.4$ K found in the temperature dependence of the transverse resistance R_{xx}. The different minima in the transverse conductance G_{xx} of the different samples show a universal temperature dependence (logarithmic in a large range of rescaled temperatures T/T_0) which is reminiscent of electron-electron-interaction effects in coherent diffusive transport.

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For a two-dimensional (2D) electron system it is well known that the discrete Landau level spectrum of an electron in a quantizing magnetic field leads to quantized magnetotransport [1]. In the Integer Quantum Hall Effect (IQHE) quantized plateaus are observed in the Hall conductance and Hall resistance ($G_{xy} = 1/R_{xy} = ie^2/h$ with integer i) together with zero-valued transverse conductance G_{xx} and transverse resistance R_{xx} at magnetic fields where the Fermi level lies at localized states in between the Landau levels. In this work, experimental evidence is given that an IQHE can also result from electron-electron interaction effects in a disordered layer with a continuous three-dimensional (3D) single-particle spectrum of the charge carriers.

Recently, a quantization of the Hall conductance has been observed in disordered epitaxial layers of heavily doped n-type GaAs with a thickness around 100 nm [2]. At 4.2 K, the magnetoresistance of these samples shows the typical behavior of bulk material with weak Shubnikov-de Haas oscillations for increasing field B and a strong monotonous upturn in the extreme quantum limit (EQL) where only the lowest Landau level is occupied. Below 1 K, the magnetic-field dependence of the Hall conductance G_{xy} shows steps at quantized values ie^2/h with i=2, 4, and 6 together with pronounced minima in the transverse conductance G_{xx} in the extreme quantum limit of the applied magnetic field, while the amplitude of the usual Shubnikov-de Haas oscillations below the EQL do not depend on temperature T below 4 K.

Ignoring quantum electron-electron correlation effects, the electronic system in the investigated GaAs layers has a 3D Landau-level spectrum without variations of the density of states due to dimensional quantization across the layer. The 3D character has been confirmed in experiments in a tilted magnetic field [3]. The magnetoresistance R_{xx} at $T = 4.2$ K shows only an insignificant change by rotating the field away from the vertical orientation. At low temperatures, the minima in R_{xx} and dR_{xy}/dB shift much slower to higher fields and are suppressed much faster as compared to the expected angular dependence for a two-dimensional system [3]. We note however, that below 3 - 4 K the characteristic diffusion lengths, $L_\varphi = (D_{zz}\tau_\varphi)^{1/2}$ and $L_T = (D_{zz}\hbar/k_B T)^{1/2}$, for coherent transport increase to values larger than d, and the system becomes 2D for coherent phenomena in the diffusive transport (D_{zz} is the diffusion coefficient of electrons along the magnetic field, τ_ϕ is the phase relaxation time).

On different Si-doped GaAs layers (thicknesses 50 - 140 nm and charge-carrier concentrations 0.8 - 1.5 $\times 10^{17}$ cm^{-3}) the temperature dependence of the QHE has been investigated. Both the observed excitation gap and universal scaling behavior in the temperature dependence of the conductance reveal the importance of electron-electron interaction effects for the explanation of the phenomenon.

The samples (see Table 1) used were prepared by molecular-beam epitaxy. Samples 1-3 are described in reference [2]. Sample 4 has the same structure as samples 2 and 3 but was grown at a somewhat higher temperature than the optimal one. Samples 5-7 have a slightly different structure: on a GaAs (100) substrate were successively grown an undoped GaAs layer (0.1 μm), a periodic structure 30 $\times$ GaAs/AlGaAs(10/10 nm), an undoped GaAs layer (0.5μm), the heavily Si-doped GaAs of nominal thickness $d = 50, 100$ and 140 nm and donor(Si) concentrations 1.5×10^{17} cm^{-3} and a cap layer (0.5 μm). Hall bar geometries of width 0.2 mm and length 2.8 mm were etched out of the wafers. A phase sensitive ac-technique was used for the magnetotransport measurements down to 50 mK. In the experiments the applied magnetic field up to 23 T was directed perpendicular to the layers.

The bulk density of electrons n in a heavily doped layer has been determined from the periodicity of Shubnikov-de Haas oscillations in the transverse resistance R_{xx} with the results as listed in Table 1 for all investigated samples. The mobilities μ have been determined from the zero-magnetic-field resistance and the Hall resistance R_{xy} in the linear region of weak magnetic fields at $T = 4.2$ K (see Table 1). They are close to the mobilities found for bulk material with comparable electron densities [4] except the mobility of sample 4 with a somewhat lower value. The average thickness d_{ex} of the conducting layers (see Table 1) has been obtained by dividing the electron density N_s per area unit, as determined from the Hall measurements, by the bulk density n. The values of d_{ex} for the investigated samples are somewhat smaller than the nominal thicknesses due to the decreasing electron density near the interfaces.

In Fig.1 the magnetotransport data of the Hall resistance R_{xy} and transverse R_{xx} (per square) have been plotted for the thinnest sample 5 at temperatures below 4.2 K. The Hall resistance R_{xy} reveals a wide plateau from $B = 7$ T up to 11 T at the lowest temperatures with the value $R_{xy} = h/2e^2$ (i.e. $i = 2$), while R_{xx} reveals a deep minimum. For samples 1,2, 4 and 6 the resistance minima at the Hall plateaus do not descend to zero, neither are the Hall plateaus completely flat (see the data in ref. [2]). Such a behavior is also seen in the QHE for 2D systems in case of a not complete opening of the mobility gap in between the Landau levels. For samples 3 and 7, only weak temperature-dependent variations are observed at the Hall plateaus with $i = 4, 6, 8$ and $i = 2, 4, 6, 8$, respectively.

In Fig.2 we have summarized the temperature dependence of the conductance for all samples investigated (except sample 1 to avoid too densily packed data points) by plotting the conductance $G_{xx,min}$ (per square) at the minima as a function of T/T_0 for temperatures from 0.07-0.1 K up to 1 K at the different Hall-conductance plateaus with $i = 2$, 4, or 6. For the minimum corresponding to $i = 2$ of sample 2, the value T_0 was taken to be 1 K. For the other temperature dependencies, the scaling parameter T_0 was chosen such in order to bring all the $G_{xx,min}(T)$ curves together. Over a large range of T/T_0 the temperature dependence of the conductance $G_{xx,min}$ is close to logarithmic and described by

$$G_{xx,min}(T) = e^2/h \left(1.32 + \frac{1.13}{\pi} \ln \frac{T}{T_0}\right) . \tag{1}$$

Above 1 K, the temperature dependences deviate from the logarithm one with reduced values near 4 K. The scaling factors T_0 depend on the conductance $G_{xx,0}$ at $T = 4.2$ K in the applied magnetic field, at which temperature interference effects are expected to be unimportant. As shown in Fig.3, the values of T_0 are well described by the dependence

$$T_0 = 117 \exp(-3G_{xx,0}h/e^2) \text{ [K]} . \tag{2}$$

Note, that Eq.(2) results automatically from the procedure of matching logarithmic curves like Eq.(1). If the logarithmic dependences of Eq.(1) would continue up to 4.2 K, the numeric coefficients in Eq.(2) would be $4.2 \exp(1.32\pi/1.13) = 165$ and $\pi/1.13 = 2.78$ instead of 117 and 3, respectively.

The obtained logarithmic temperature dependence of the conductance is well known from the small corrections to the conductance as a result of electron-electron interaction effects in the case of coherent diffusive transport in 2D [5]. In our case the temperature dependences in the minima are close to logarithmic even for strong changes of the conductance. The coefficient in the logarithmic term of Eq.(1) is somewhat larger than the maximum value $1/\pi$ in the perturbation theory of small corrections [5]. Only for the thickest sample 7 the changes in the minima of G_{xx} are small (about 5%) with a better description of the logarithmic temperature dependence using the coefficient $1/\pi$. The temperature dependence of the conductances G_{xx} and G_{xy} for sample 2 and 3, in lower magnetic fields ($B < 8$ T) where $G_{xx,0} > 4e^2/h$, show a good description in terms of quantum corrections of electron-electron-interaction effects [6].

There is no theory of electron-electron interactions in the diffusive transport beyond the limit of small corrections. However, we note that a logarithmic temperature dependence with a strong decrease of G_{xx} was observed in pure 2D GaAs/AlGaAs heterostructures in the maxima of G_{xx} [7]. It was interpreted as a result of electron-electron interaction effects [7,8].

Sample 5, showing the strongest Quantum Hall Effect structures, has an activated behavior of the resistance $R_{xx} \propto \exp(-E_A/T)$ at temperatures below 0.2 K ($T/T_0 < 0.02$ in Fig.2) with an activation energy $E_A = 0.4$ K (see insert Fig.1). The large width of the Hall plateau (from $B = 7$ T up to 11 T) in sample 5 compared to the small gap in the activated behavior of the resistance minimum indicates that there is a Coulomb gap at low temperatures which moves together with the Fermi level when the magnetic field changes. All energy scales in the single-particle approach, except spin-splitting, are much larger than $E_A = 0.4$ K. The Fermi energy E_F in zero magnetic equals 140 K, the scattering-induced broadening $\hbar/\tau = 100$ K, the cyclotron energy $\hbar\omega_c = 180$ K, and the distance $3(\pi\hbar/d)^2/2m$ between the lowest levels of dimensional quantization in a pure layer of the same 50-nm thickness equals 80 K. The spin-splitting can hardly be important for even i. The narrow gap can be induced only by electron-electron correlations with a large correlation length. In the case of a narrow single-particle mobility gap non-attached to the Fermi level, the Hall plateau would be expected to be very narrow because E_F changes about 2 times in the field range 7-11 T.

In Fig.2 we have also plotted the conductance $G_{xx,max}$ for the maxima in between the quantized minima (denoted by odd numbers in the legenda) and between the minima with $i = 2$ and an insulator state at higher fields (denoted by 1). Using the same Eq.(2) for the calculation of the rescaled T/T_0 as for the minima, the data for the maxima also show a universal behavior for the samples with $G_{xx,0} > 1.5e^2/h$. The data for the maxima have somewhat lower values for the samples with $G_{xx,0} < 1.3e^2/h$ (samples 4 and 5) .

The possibility of a Hall-conductance quantization in a system with a continuous spectrum has been suggested by Khmel'nitskiĭ [9] in the frame of non-interacting quasi particles. According to this approach, in a layer (film) with high-temperature conductances in a magnetic field such that $G_{xx,0}$ and $G_{xy,0} \gg e^2/h$, the conductance G_{xx} decreases due to quantum coherent (localization) effects when the temperature goes down. At the beginning the decrease is described by second order quantum corrections [10,6]. When G_{xx} becomes of order e^2/h, the quantization of G_{xy} should develop.

However, in a layer with $G_{xx,0}$ and $G_{xy,0} \gg e^2/h$ the quantum corrections to G_{xx} due to electron-electron correlations (of the first order) are much larger than that due to the single-particle localization effects (of the second order). A calculation of these latter single-particle corrections to the conductivity of our samples [6] results in a much weaker temperature dependence of G_{xx} than experimentally observed even in the regions of magnetic fields where the QHE structure is observed. Since $\log T$ diverges at $T \rightarrow 0$, one may expect that the enhancement of interaction effects with decreasing temperature results in a Coulomb gap at the Fermi level with a vanishing dissipative conductance G_{xx} in some ranges of the magnetic field. In this case the Hall conductance should be quantized according to Laughlin's argument [11], which has also validity for a three dimensional system [12]. Since there is no designated value of i, G_{xy} will apparently approach the most nearby quantized value as temperature decreases. In between, transitional regions should exist where G_{xy} is not quantized and, correspondingly, G_{xx} approaches a constant value. Our experimental results indicate that this scenario is realized.

In summary, the large width of the Hall plateau at a small excitation gap is a strong evidence that the novel phenomenon of an IQHE in disordered GaAs layers with a three-dimensional single-particle spectrum is induced by electron-electron interactions. The observed logarithmic temperature dependence in the universal T/T_0 dependence of the conductance minimum $G_{xx,min}$, with T_0 only depending on the high-temperature conductance $G_{xx,0}$, is a continuation of the small logarithmic quantum corrections of electron-electron interactions in the diffusive transport.

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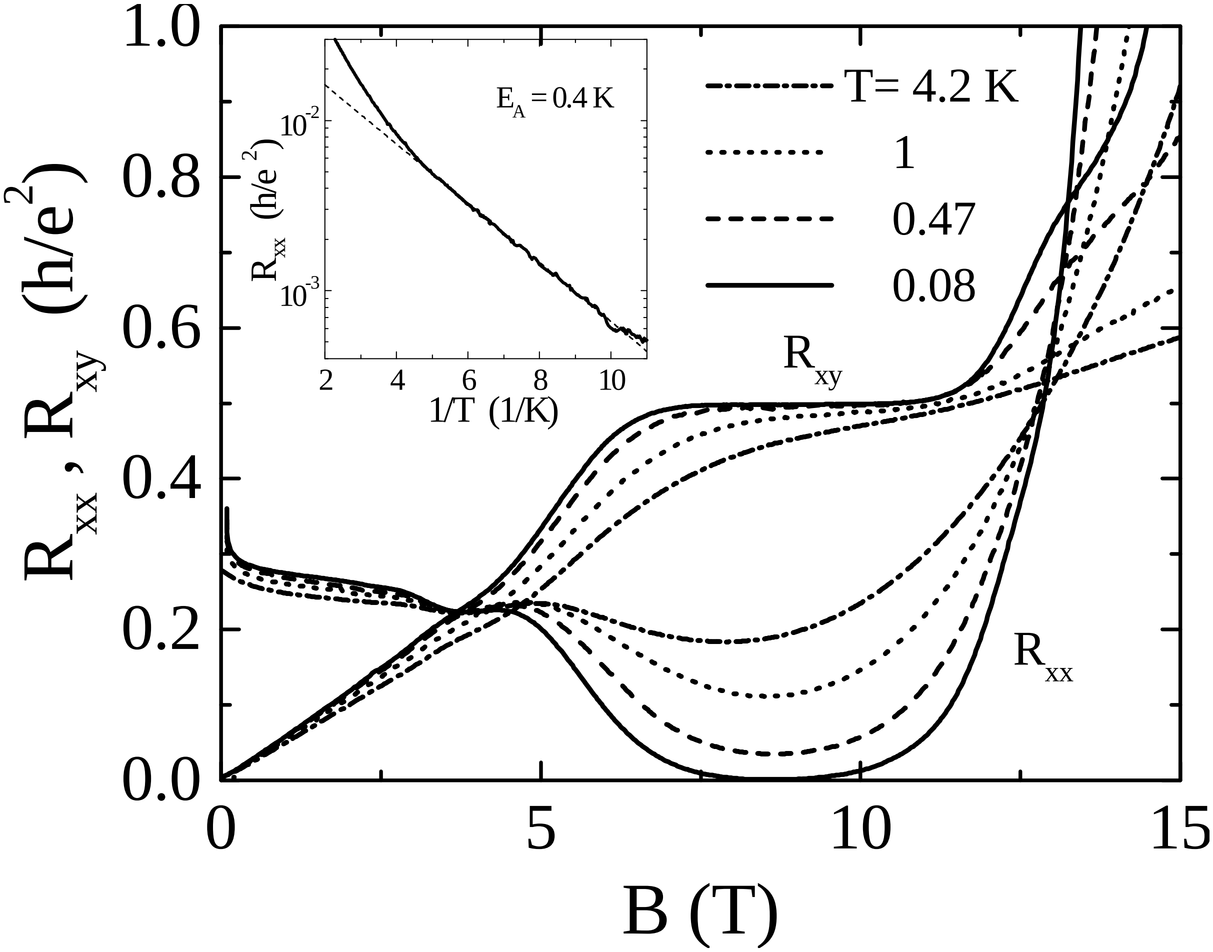

FIG. 1. Magnetic field dependence of the Hall resistance R_{xy} and transverse resistance R_{xx} (per square) for sample 5 in a magnetic field perpendicular to the GaAs layer at two temperatures. R_{xy} reveals a wide plateau at $h/2e^2$ from $B = 7$ T up to 11 T at low temperatures with a deep minimum in R_{xx}. The insert shows an activated behavior $R_{xx} \propto \exp(-E_A/T)$ with $E_A = 0.4$ K for temperature dependence in minimum at $B = 8.65$ T.

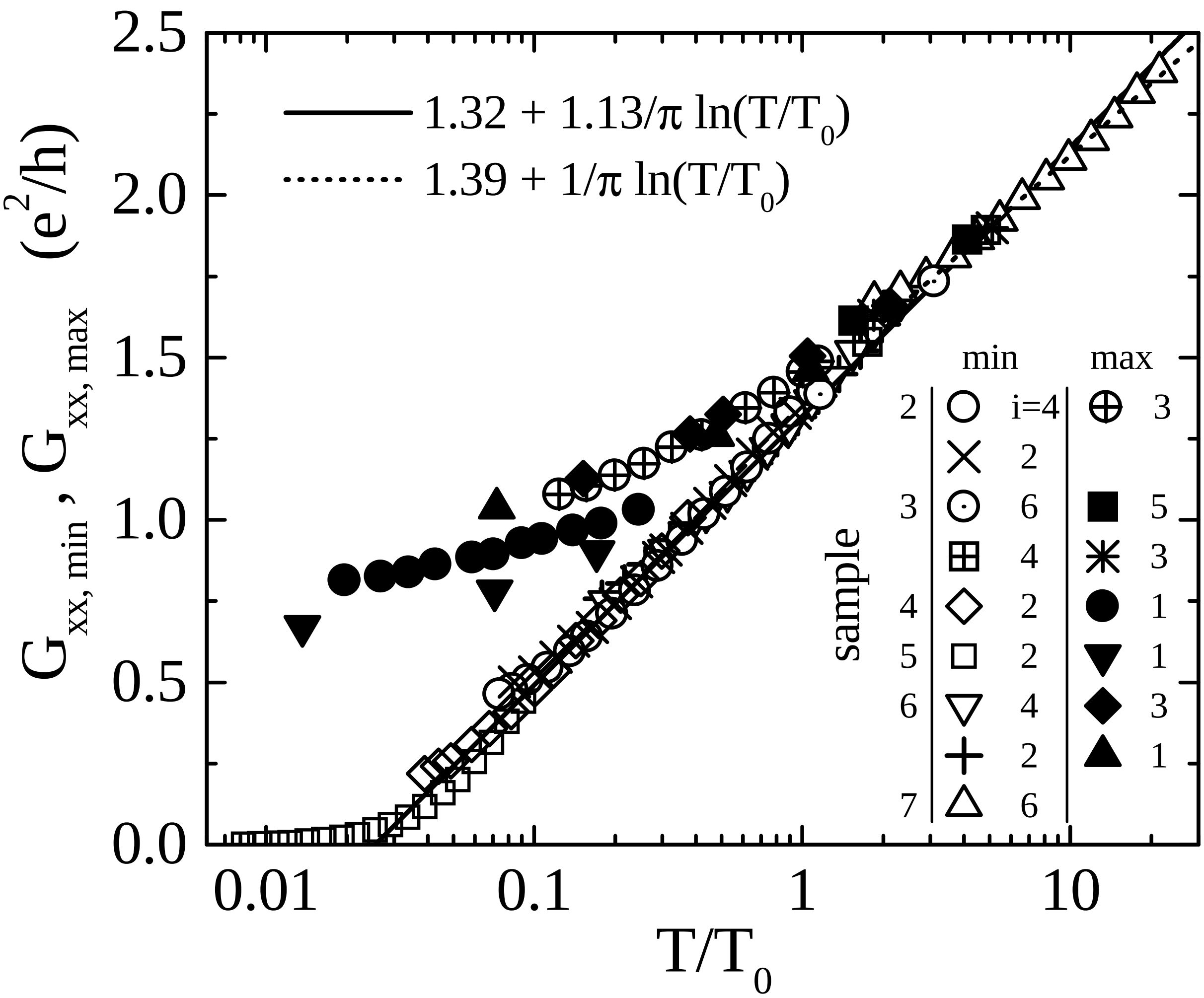

FIG. 2. Conductance $G_{xx,min}$ at the minima and $G_{xx,max}$ at the maxima as a function of the normalized temperature T/T_0 for different minima and maxima in different samples. The straight solid and dash lines correspond to the dependences $G_{xx,min} = e^2/h[1.32+1.13/\pi\ \ln{(T/T_0)}]$ $G_{xx,min} = e^2/h[1.39 + 1/\pi\ \ln{(T/T_0)}]$, respectively, at the minima. In the legend, the first column indicates the sample number, the second gives the data symbols for the minima at even quantum numbers i ($G_{xy} = ie^2/h$) and the third the data symbols for the maxima denoted by odd numbers. The values of the magnetic field for the minima are, successively, 11.8, 17.7; 14, 20; 7.1; 8.65; 11.6, 16.9; 10.4 T and for the maxima 14.3; 16.8, 22.5; 9.3; 12.6, 14, 19 T .

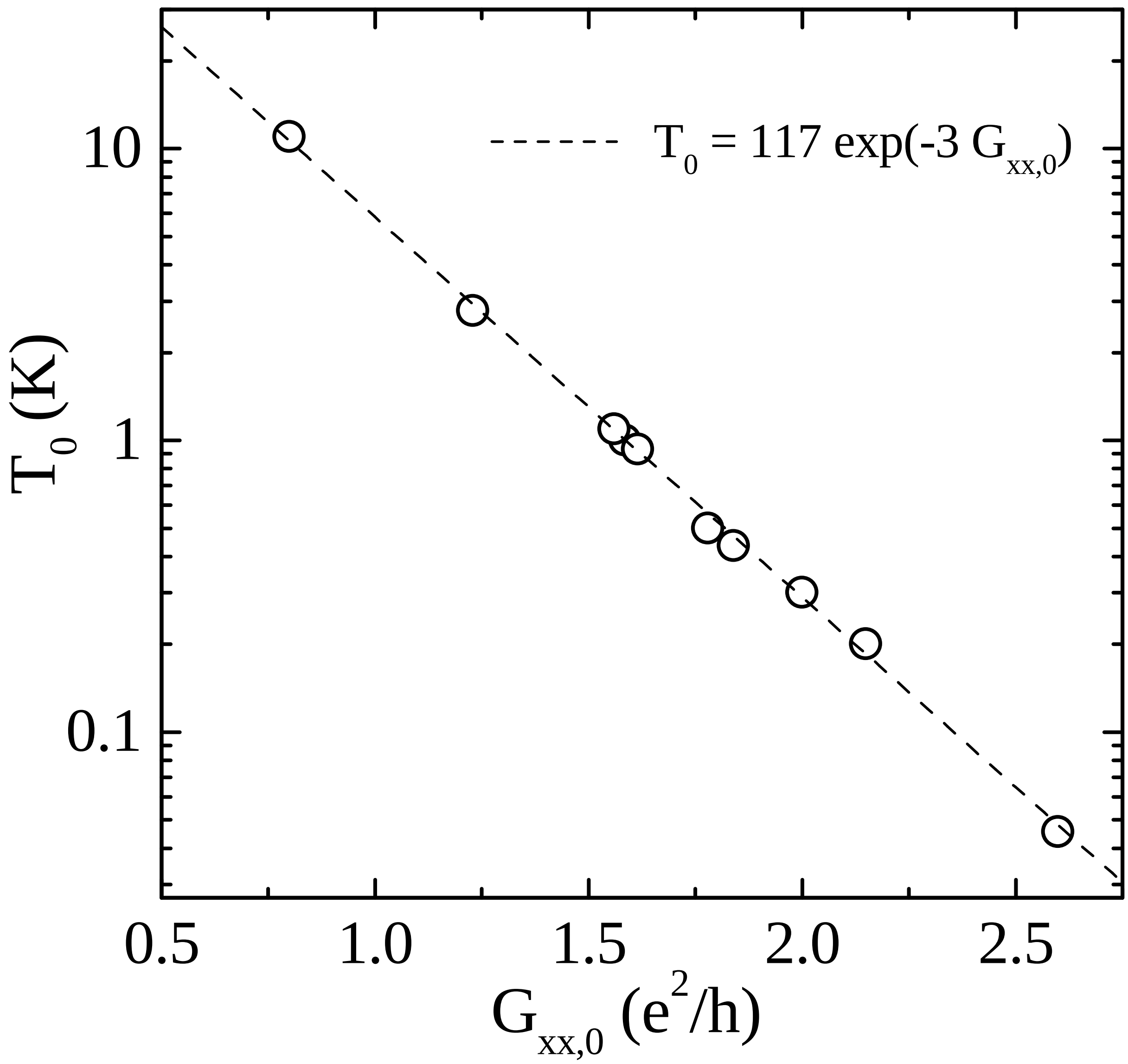

FIG. 3. Logarithm of the scaling factor T_0 as a function of the conductance $G_{xx,0}$ at $T = 4.2$ K as deduced from the data presentation in Fig.(2).

TABLES

Sample	n (cm^{-3})	μ (cm^2/Vs)	d_n (nm)	d_{ex} (nm)	i	$G_{xx,0}(e^2/h)$
1	0.8×10^{17}	1900	100	70	2	1.56
2	1.8×10^{17}	2400	100	70	2	1.62
					4	1.59
3	2.5×10^{17}	2500	100	80	4	2.15
					6	2
4	0.85×10^{17}	1000	-	50	2	1.23
5	1×10^{17}	1900	50	50	2	0.8
6	1.6×10^{17}	2600	100	80	4	1.84
					6	1.78
7	1.6×10^{17}	2600	140	110	6	2.6