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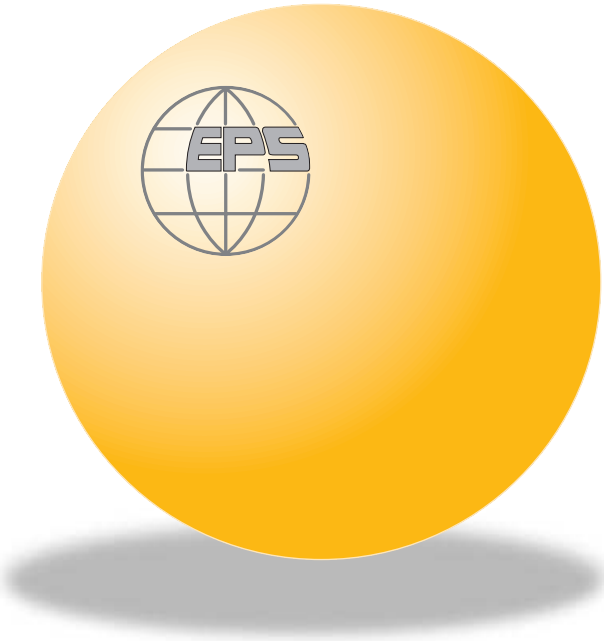

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Hot-hole effects in a dilute two-dimensional gas in SiGe

R. Leturcq[1], D. L'Hôte[1], R. Tourbot[1], V. Senz[2], U. Gennser[3], T. Ihn[2], K. Ensslin[2], G. Dehlinger[4] and D. Grützmacher[4]

[1] *DSM/Service de Physique de l'Etat Condensé, CEA-Saclay 91191 Gif-sur-Yvette Cedex, France*

[2] *Laboratory of Solid State Physics, ETH Zürich - CH-8093 Zürich, Switzerland*

[3] *Laboratoire de Photonique et de Nanostructures, CNRS - 91460 Marcoussis, France*

[4] *Paul Scherrer Institut - CH-5232 Villigen PSI, Switzerland*

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Abstract. – We study the resistivity *vs.* electric-field dependence $\rho(E)$ of a dilute two-dimensional hole (h) system in SiGe, on both sides of the crossover from weak to strong localization at $B = 0$. Using ρ as a "thermometer" to obtain the effective temperature of the holes $T_e(E)$, we find that $\rho(E)$ can be attributed to hole heating. In spite of the strong localization and h-h interactions, the power loss does not indicate any deviation from the density and temperature dependences predicted assuming independent and delocalized electrons. The consequences of these results on the h-h interaction assisted hopping, glassy behaviour and E-field scaling are developed. The hole-phonon coupling involves a limited screening, a deformation potential compatible with measurements at larger densities and temperatures, and a piezoelectric component which is definitely probed.

Electron-phonon (e-p) interaction is a fundamental process in the physics of low-temperature two-dimensional electron or hole systems (2DES or 2DHS). It determines the carriers effective temperature T_e when a given power per carrier P_E flows from them to the lattice at a temperature T_l. The power loss P_E has been studied both experimentally and theoretically for 2DES or 2DHS realized at semiconductor heterostructures or in silicon metal-oxide-semiconductor field effect transistors (Si-MOSFETs) [1–11]. These studies have involved weakly localized carriers (at magnetic field $B = 0$) in the diffusive regime where the Fermi liquid description is valid, together with e-p interactions due to deformation or piezoelectric potentials, which can be screened by the 2DES. The heating effects explain the resistivity *vs.* electric-field dependence $\rho(E)$. However, less is known about the strongly localized regime which is reached in a dilute 2DES. The localization and the strong e-e interactions at low densities should affect the matrix element of the e-p coupling and the screening properties of the 2DES, raising the question whether the power loss has the same temperature and density dependences as in the weakly localized regime, and if there are additional electric-field effects. Indeed, in a strongly localized system characterized by variable-range hopping (VRH), E-field effects due to hopping along the field direction are predicted [12–14]. The interplay of E-field and heating effects have been studied for a long time in 3D insulators [14], but they have

been only recently considered by Gershenson *et al.* for a 2DES with strong localization (SL), in n-GaAs [12]. The parameters ρ_0, T_0 and p of the VRH law [13]

$$\rho(T) = \rho_0 \exp[(T_0/T)^p] \tag{1}$$

give a clue to the importance of e-e interactions. The latter lead to the Coulomb gap, thus $p = 1/2$ [13] which has been found in Si-MOSFETs [15–17] and n-GaAs [18–20]. The low-T_0 values [19, 21], and universal prefactors ρ_0 [18, 19] suggest e-e interaction assisted hopping. The importance of the interactions has also been stressed by the possible existence of a metal-insulator transition (MIT) for $5 < r_s < 40$, r_s being the ratio of the e-e interaction energy to the Fermi energy ($r_s \propto m^*/p_s^{1/2}$, m^* is the effective mass and p_s the density) [22]. Although the "metallic" behaviour could be due to quasi-classical processes masking the weak localization (WL) [23–26], the existence of a correlated electron system due to the strong interactions [22, 27–31], such as a glass [28, 30–33], remains an important issue.

Also in the WL regime the power loss deserves further attention. Although the predicted power law temperature dependences of P_E have been confirmed by experiments, discrepancies between the measured and calculated e-p potentials have been found in Si-MOSFETs [4–6] and in p-SiGe. A piezoelectric effect has been measured in spite of the covalent nature of silicon and the normally random distribution of the Ge atoms in SiGe alloys [6, 10, 11]. Furthermore, unexpected weak screening has been found in p-SiGe [10, 11] and Si MOSFETs [4–6].

In this paper, we demonstrate experimentally that for a 2DHS in p-SiGe, the $\rho(E)$-dependence can be attributed to hole heating all along the crossover from the diffusive to the VRH regimes. The crossover density p_c corresponds to a large r_s (≈ 6), contrary to n-GaAs. The power loss $P_E(T_e, T_l)$ is compatible with the standard heating models [1, 2] for all densities investigated. The extracted hole-phonon (h-p) deformation potential is close to the values obtained for densities 2.5 to 10 times larger [10, 11]. The piezoelectric coupling is clearly probed [10, 11], and the absence of strong screening is discussed. We show that the heating interpretation in the VRH regime has consequences in terms of h-h interaction assisted hopping and glassy behaviour. Finally, we suggest how to disentangle heating effects from E-field scaling in the case of a MIT [22, 34].

The experiments were performed on 2DHS with an effective mass $m^* \approx 0.25 m_0$, realized at a $Si/Si_{0.85}Ge_{0.15}$ interface of p-SiGe quantum wells [24, 35]. Two gated Hall bars (S1 and S2) were used, the gate-2DHS distance being $d = 53\,\text{nm}$. Their width W is $100\,\mu\text{m}$, and their length L (between voltage probes) $233\,\mu\text{m}$ for S1, and $125\,\mu\text{m}$ for S2. By varying the gate voltage, their densities were tuned between 0.8 and $1.7 \times 10^{11}\,\text{cm}^{-2}$. The mobilities ($\mu$) at 200 mK increase with p_s from 600 to $5500\,\text{cm}^2/\text{Vs}$ (respectively 1000 to $7400\,\text{cm}^2/\text{Vs}$) for S1 (respectively S2). We present here mainly the more accurate data from S1. An ungated sample ($p_s = 3.9 \times 10^{11}\,\text{cm}^{-2}$, $\mu = 7800\,\text{cm}^2/\text{Vs}$) has also been used. The temperature range was 70 mK–1.4 K. To check that the temperature T of the thermometer fixed in the copper sample holder was that of the lattice T_l, the low-current resistance of another Hall bar etched onto the same substrate was used as a thermometer. Its temperature remained close to T whatever the current in our samples. $\rho = (V/I)(W/L)$ and $E = V/L$ were obtained from the current I and the voltage drop V between the voltage probes, using a four-point DC technique, with a current (10–300 pA for low E) periodically reversed at a frequency 0.03–0.3 Hz.

Figure 1 (a)-(e) shows the two transport regimes below and above $p_c \approx 1.3 \times 10^{11}\,\text{cm}^{-2}$ ($r_s \approx 6$ and $k_F l \approx 1.3$, k_F is the Fermi wave vector and l the hole mean free path). For $p_s < p_c$, ρ decreases strongly when T increases, while for $p_s > p_c$, a weak decrease is followed by a weak increase. The latter has been considered as an indication of a new metal [22, 35], however, $\rho^{-1}(T)$ can be described as the sum of the Drude conductivity with temperature-dependent

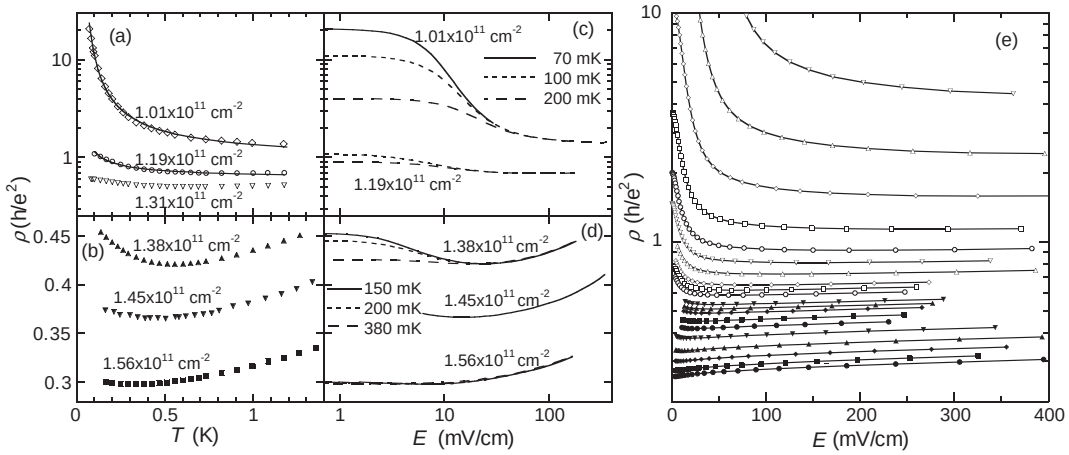

Fig. 1 – (a), (b) The resistivity ρ *vs.* temperature (for $E \to 0$), at different densities p_s. The continuous lines in (a) are fits to eq. (1). (c), (d) ρ *vs.* E-field for various p_s and T_l values. (e) ρ *vs.* E for $T_\mathrm{l} = 120\,\mathrm{mK}$, and p_s ranging from $0.92 \times 10^{11}\,\mathrm{cm}^{-2}$ (top curve) to $1.75 \times 10^{11}\,\mathrm{cm}^{-2}$ (bottom).

screening (giving $\mathrm{d}\rho/\mathrm{d}T > 0$) and quantum corrections ($\mathrm{d}\rho/\mathrm{d}T < 0$) [24], indicating that the Fermi-liquid concept is valid in spite of such a large r_s. For $p_s < p_\mathrm{c}$, the VRH is probed by the fit of $\rho(T)$ with eq. (1), assuming $\rho_0 \propto T^m$ [12, 13, 20]. We obtain $m \approx 0.7$–1.1 if $p = 1/2$ is imposed. The two regimes appear also in the $\rho(E, p_s)$ curves (fig. 1(c)-(e)), with the *same* crossover density p_c. The general shape and the minima of $\rho(E)$ and $\rho(T)$ are the same, suggesting hot-hole effects. They are investigated as follows: i) the $\rho(E)$-dependence is assumed to result from Joule heating that leads to a hole temperature T_e larger than the lattice temperature T_l; ii) $\rho(E)$ is used as a "thermometer" giving T_e as the temperature T at which the same value of ρ is measured for $E \to 0$; iii) the relationship between T_e and the power per carrier $P_E = VI/(p_s WL) = E^2/(\rho p_s)$ is used to study the validity of the hot-carrier assumption i). Figure 2(a) shows the $P_E(T_\mathrm{e})$-dependence for densities above and below p_c.

The calculation of the power loss between the 2DES and the lattice acoustic phonons in the Bloch-Grüneisen limit ($q \ll k_\mathrm{F}$, with q the thermal phonon wave vector) gives [1, 2]

$$P_E(T_\mathrm{e}, T_\mathrm{l}, p_s) = A(p_s)(T_\mathrm{e}^{\alpha} - T_\mathrm{l}^{\alpha}) + A'(p_s)\big(T_\mathrm{e}^{\alpha'} - T_\mathrm{l}^{\alpha'}\big). \tag{2}$$

The first term corresponds to the deformation potential, with $\alpha = 5$ (respectively 7) for weak (respectively strong) screening. The second term is piezoelectric coupling, to be considered for coherently strained SiGe [10, 11, 36, 37], with $\alpha' = 3$ (respectively 5) for weak (respectively strong) screening. $\alpha = 6$ and $\alpha' = 4$ are obtained in the case of "dynamic" rather than "static" screening [3]. A and A' are related to the e-p coupling constants; they are proportional to $p_s^{-3/2}$ for weak or strong screening, and to ρ for dynamic screening [3]. We verified that in our T_l and p_s ranges, $q/k_\mathrm{F} < 0.15$. To test the validity of eq. (2) for our measurements, we write it: $P_E + (AT_\mathrm{l}^{\alpha} + A'T_\mathrm{l}^{\alpha'}) = (AT_\mathrm{e}^{\alpha} + A'T_\mathrm{e}^{\alpha'})$. Figure 2(b) shows that by adding to P_E a constant $P_0(T_\mathrm{l})$ chosen separately for each T_l, the whole set of curves for a given density falls on the same master curve. Hence $P_E(T_\mathrm{e}, T_\mathrm{l}) + P_0(T_\mathrm{l})$ depends only on T_e, and this dependence is the sum of two power laws. We have verified that the $P_0(T_\mathrm{l})$-dependence is *the same*, thus proving that our data are in agreement with eq. (2). Figure 2(b) shows that a power law with $\alpha' \approx 3$ (respectively $\alpha \approx 5$–6) dominates at low (respectively large) T_e. Similar results are obtained for all densities and samples, however α' lies between 2 and 3 for $p_s \geq 1.38 \times 10^{11}\,\mathrm{cm}^{-2}$. We

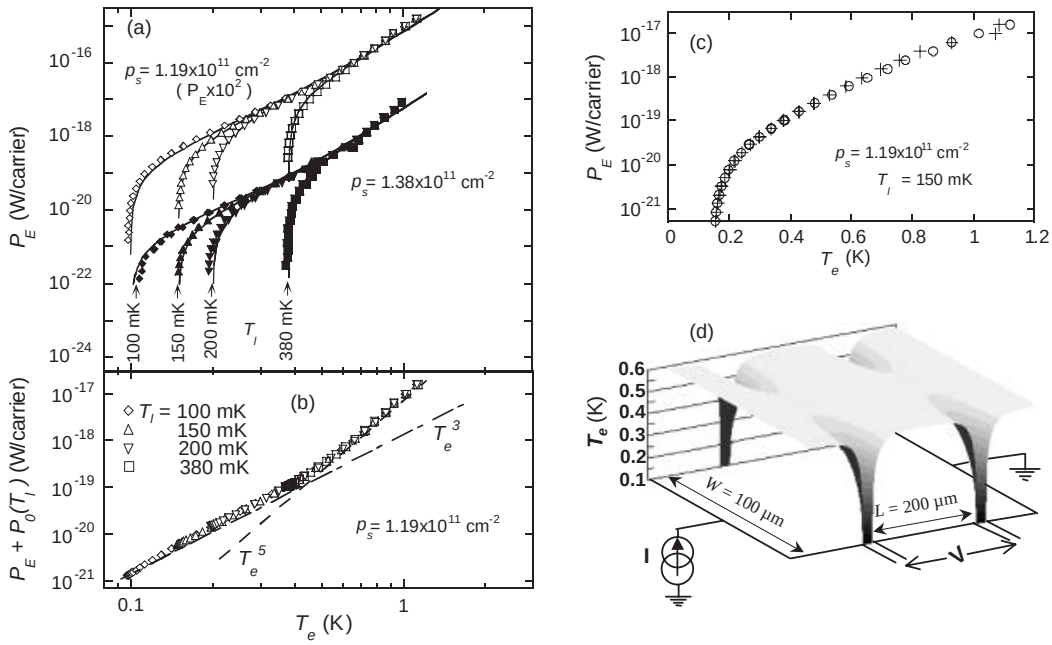

Fig. 2 – (a) The Joule power per hole P_E as a function of the hole effective temperature T_e, for two densities below and above p_c, at several lattice temperatures T_l (arrows). For clarity, the curves corresponding to $p_s = 1.19 \times 10^{11}\,\mathrm{cm}^{-2}$ are shifted upwards by 100. The lines corresponding to the lower density are fits to $P_E = A(T_\mathrm{e}^5 - T_\mathrm{l}^5) + A'(T_\mathrm{e}^3 - T_\mathrm{l}^3)$; while for the larger density, a term corresponding to contacts cooling is added in the fit. (b) The sum of P_E and a constant $P_0(T_\mathrm{l})$ chosen for each T_l, as a function of T_e, for various T_l values indicated in the figure. The lines give the slopes of the power laws T_e^3 and T_e^5. (c) P_E as a function of T_e extracted using the ρ thermometer at $B = 0$ ($\circ$) or the damping of the SdH oscillations (+). (d) Calculated temperature profile in the Hall bar using the 2D heat equation and taking into account the cooling through the four voltage contacts, for $p_s = 1.38 \times 10^{11}\,\mathrm{cm}^{-2}$, $T_\mathrm{l} = 100\,\mathrm{mK}$ and $P_E = 3 \times 10^{-19}\,\mathrm{W/carrier}$.

attribute this to the cooling through the contacts which increases when ρ decreases [4]. It can be taken into account by adding a term $A''(T_\mathrm{e}^2 - T_\mathrm{l}^2)$ in eq. (2) [4]. Fits with such a term yield a value of A'' close (within a factor 2) to the value calculated using the one-dimensional heat equation [4]. To evaluate more accurately this effect, we have solved numerically the two-dimensional heat equation in the Hall bar, using the Wiedeman-Franz law and eq. (2) (see fig. 2(d)) [38]. This calculation with $\alpha' = 3$ gives a $P_E(T_\mathrm{e}, T_\mathrm{l})$ law in perfect agreement with the data. In what concerns α, the number and accuracy of the data points at large T_e do not allow to distinguish between 5 and 6, except for $p_s \leq 1.31 \times 10^{11}\,\mathrm{cm}^{-2}$, where $\alpha = 5$ is favoured. Figure 2(a) shows the quality of the fit with eq. (2) when $\alpha = 5$ and $\alpha' = 3$ are imposed. To further prove the validity of the heating analysis, T_e extracted at $B = 0$ is compared to the value obtained using the damping of the SdH oscillations [4, 5, 7, 10, 11]. To get rid of the $\rho_{xx}(T)$-dependence due to carrier-carrier scattering [7], the "thermometer" is the difference between a minimum of $\rho_{xx}(B)$ and the previous maximum. Its T-dependence results from a different physical situation (the density of states oscillations) than at $B = 0$. The low magnetic field ($B \approx 1\,\mathrm{T}$) allows h-p couplings close to those at $B = 0$ [7]. As shown in fig. 2(c) for $p_s = 1.19 \times 10^{11}\,\mathrm{cm}^{-2}$ and $T_\mathrm{l} = 150\,\mathrm{mK}$, the two methods are in very good agreement. A similar agreement is obtained for other T_l values and for $p_s = 3.9 \times 10^{11}\,\mathrm{cm}^{-2}$.

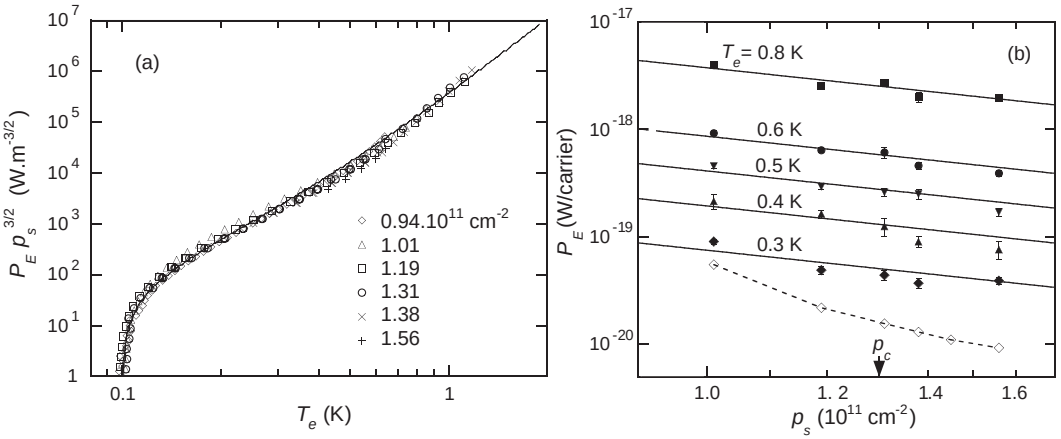

Fig. 3 – (a) P_E times $p_s^{3/2}$ as a function of T_e for six densities p_s indicated in the figure, and $T_\mathrm{l} = 100\,\mathrm{mK}$. The points where contacts cooling is significant have been suppressed. The full line is a fit with eq. (2), $\alpha = 3$ and $\alpha' = 5$. (b) P_E *vs.* p_s for various values of T_e. The lines are fits of a power law with the exponent $-3/2$. The open diamonds and the dashed line give $\rho(T_\mathrm{e} = T_\mathrm{l} = 500\,\mathrm{mK})$ multiplied by an arbitrary factor, as a function of p_s.

Fits with eq. (2) assuming $\alpha = 5$ and $\alpha' = 3$, together with the weak screening relations [1, 2, 10] ($A \propto \Xi_u^2/p_s^{3/2}$ and $A' \propto e_\mathrm{pz}^2/p_s^{3/2}$, with Ξ_u and e_pz the deformation and piezoelectric coupling constants) yield $\Xi_u = 2.7 \pm 0.3\,\mathrm{eV}$ and $e_\mathrm{pz} = (3.4 \pm 0.9) \times 10^{-3}\,\mathrm{C/m^2}$ for all the densities. Figure 3 shows that the data are compatible with the $p_s^{-3/2}$-dependence. Our Ξ_u value is close to the $\Xi_u \approx 3.0\,\mathrm{eV}$ found in p-SiGe at $p_s = (3.5\text{–}13) \times 10^{11}\,\mathrm{cm^{-2}}$ [10, 11]. Our low-temperature range allows to give a positive answer to the question of the existence of piezoelectric coupling in p-SiGe [10, 11]. The latter is expected from the displacement of the electronic charges relative to the Si or Ge cores, when an order is due to the strain. Our e_pz is lower than the $e_\mathrm{pz} \approx 1.6 \times 10^{-2}\,\mathrm{C/m^2}$ obtained in p-$Si_{0.8}Ge_{0.2}$ [10]; however, in ref. [11] no indication of piezoelectric coupling was found. A possible interpretation is that ordering is present in spite of the large growth temperature of the samples (800°) [11, 36, 37]. However, recently, a T^3-term was observed in the $P_E(T_\mathrm{e}, T_\mathrm{l})$ law for Si-MOSFETs [6]. As silicon is not piezoelectric, this was attributed to the lack of inversion symmetry at the Si-SiO_2 interface. They find $a = A' n_s = 2.2 \times 10^{-8}\,\mathrm{W/K^3 cm^2}$ (n_s: density), to be compared to $A' p_s = 13 \times 10^{-8}\,\mathrm{W/K^3 cm^2}$ for $p_s \approx 1.3 \times 10^{11}\,\mathrm{cm^{-2}}$ in our case. It could be that this possible new h-p coupling would explain the unexpected weak screening. As a matter of fact, an estimate of the screening function $S(Q)$ [1], Q being the projection of q on the 2DHS plane, implies a screening length lower than $1/Q$ for our Q range, $10^4\,\mathrm{cm^{-1}} < Q < 10^5\,\mathrm{cm^{-1}}$. However, as $0.02 < ql < 0.3$ for $p_\mathrm{c} < p_s < 1.6 \times 10^{11}\,\mathrm{cm^{-2}}$, dynamic screening is expected, with $\alpha = 6$ and $\alpha' = 4$ [3]. $\alpha = 6$ is not so far from the values 5-6 obtained experimentally, but $\alpha' = 4$ does not fit our results. In addition the $P_E \propto \rho$ law [3] gives a poor agreement with the data (see fig. 3(b)). Weak screening has been pointed out in p-SiGe [10, 11] and Si-MOSFETs [4–6]. An important remark here is that in the SL regime, the screening is fully efficient only for $Q\xi > 1$ [39] (ξ = localization length), thus it should be weakened when p_s and ξ decrease.

Figure 3(b) shows the smooth P_E *vs.* p_s-dependence without any sudden variation at $p_s = p_\mathrm{c}$ which could be attributed to the WL-SL crossover or to a MIT [22]. It is compatible with the $p_s^{-3/2}$ law, although the uncertainties preclude an accurate exponent extraction. The

power loss of eq. (2) results from the assumption of independent and delocalized electrons [1,2]. Thus for $p_s > p_c$ the Fermi-liquid behaviour is confirmed [24]. For $p_s < p_c$ two points are *a priori* surprizing. First, the $P_E(T_e, T_l, p_s)$-dependences remain the same as above p_c. In an independent particle picture, this can be related to the large values of ξ and $Q\xi$ [12]. Second, T_e can be obtained from the value of ρ whatever T_l. In the VRH theory [13], ρ depends both on T_e and T_l, as the energy of a jump between two localized sites is exchanged with the phonons. Marnieros *et al.* [40] concluded from the independence of ρ *vs.* T_l in a three-dimensional insulator that the VRH should be assisted by e-e interactions. A similar interpretation was considered for n-GaAs 2DEG [12]. Its consequences on the physics of the 2DHG can be developed further. The system which provides or absorbs the energy of an e-e interaction assisted jump must have a continuous spectrum in order to give the exact amount needed. The spectrum of the system made of the neighbour electrons is discrete as it results from the different sites occupation configurations. Thus, the jump must be accompanied *both* by simultaneous jumps of neighbour electrons *and* by e-p interactions, as assumed, *e.g.*, in ref. [41]. For the $\rho(T_l)$-dependence to be negligible, a large number of jumps must contribute to the transport for each e-p interactions. This suggests that the system is a glass [30–33]. In such a system, the interactions could lead to delocalization [33, 42]. In our case, the on-site interactions could contribute to hopping. The large ξ for p_s close to p_c and the screening of h-h interactions by the gate at distances larger than $d = 53\,\text{nm}$ [20] leads to a reduced double-site occupancy energy. Hopping via double occupied states in the upper Hubbard band has been suggested [18]. In the VRH, only the electrons belonging to the percolation paths of the Miller-Abrahams network [13] contribute to the transport. On the contrary, the smooth P_E-*vs.* p_s-dependence suggests that the whole 2DHS surface is heated. This again indicates the importance of the interactions which allow to share the energy among all the carriers.

Our results have consequences on the possible E-field scaling analysis in the case of a MIT at $p_s = p_c$ [22, 34]. Such a MIT is unlikely in our samples [24], but it could possibly be considered for cleaner systems [22]. ρ would scale with T and E [34]: for $\delta_n = |(p_s - p_c)/p_c| \ll 1$, $\rho(T, p_s)$ (for $E \to 0$) would depend only on $\delta_n/T^{1/z\nu}$, and $\rho(E, p_s)$ (at low T) would depend only on $\delta_n/E^{1/(z+1)\nu}$ (z and ν are the critical exponents). This is because the *smallest* of the two lengths $L_\Phi(T) \sim T^{-1/z}$ and $L_E(E) \sim E^{-1/(z+1)}$ governs the physics at the MIT. To distinguish the E scaling from the $\rho(E)$-dependences due to heating [23, 34], the ratio of the exponents in the experimental scaling laws $\rho(\delta_n/T^b)$ and $\rho(\delta_n/E^a)$ has been used [34,35]. Heating effects lead to $2/\alpha < a/b < 2/\alpha'$, while scaling gives $a/b = z/(z+1) = 0.5$. In our case, the a/b criterion is difficult to use because $2/\alpha < z/(z+1) < 2/\alpha'$. We suggest that E scaling can be studied in spite of heating effects by noticing that it prevails if $L_E(E) < L_\Phi[T_e(E)]$ [34]. As we have seen, the law $T_e(E)$ can be extracted from the data. Using our experimental $T_e(E)$ and assuming a MIT with $z = 1$ (thus $L_\Phi \sim T^{-1}$ and $L_E \sim E^{-1/2}$), we found that above a field E_c defined by $L_E(E_c) = L_\Phi[T_e(E_c)]$, the condition $L_E(E) < L_\Phi(T_e)$ is fulfilled. This is because the $L_E(E)$ curve has a steeper slope than $L_\Phi[T_e(E)]$ ($L_\Phi[T_e(E)] \propto E^{-2/5}$ for large E as can be shown from eq. (2)). Thus E_c could be extracted as the limit above which the experimental $P_E(T_e)$ law starts to differ from the power loss law. From the value of E_c, the important physical result $L_\Phi(T)/L_E(E) = [T_e(E_c)/T]^{1/z}(E/E_c)^{1/(z+1)}$ could be obtained.

In summary, we have shown that in a dilute 2DHS with $r_s \approx 6$, the $\rho(E)$-dependence can be attributed to hot-hole effects on both sides of the WL-SL crossover, with a h-p deformation coupling close to the value obtained at much larger p_s, and a piezoelectric coupling which is clearly probed [10, 11]. This heating interpretation works as if the 2DHS was made of independent and delocalized particles in spite of the SL and strong h-h interactions. This supports the e-e interaction assisted hopping and glassy behaviour. Finally, we have discussed the question of disentangling heating effects from E-field scaling in the case of a MIT.

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