Journal of Physics: Condensed Matter

PAPER

Electron heating induced by an ac-bias current in the regime of Shubnikov–de Haas oscillation in the high mobility GaAs/Al$_x$Ga$_{1-x}$As two-dimensional electron system

To cite this article: C Rasadi Munasinghe *et al* 2018 *J. Phys.: Condens. Matter* **30** 315701

IOP Publishing
Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter **30** (2018) 315701 (5pp)
https://doi.org/10.1088/1361-648X/aace34

Electron heating induced by an ac-bias current in the regime of Shubnikov–de Haas oscillation in the high mobility GaAs/Al$_x$Ga$_{1-x}$As two-dimensional electron system

C Rasadi Munasinghe[1], **B Gunawardana**[1], **R L Samaraweera**[1], **Z Wang**[1], **T R Nanayakkara**[1], **A Kriisa**[1], **C Reichl**[2], **W Wegscheider**[2] and **R G Mani**[1]

[1] Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303, United States of America
[2] Laboratorium für Festkörperphysik, ETH Zürich, CH-8093 Zürich, Switzerland

E-mail: rmani@gsu.edu

Received 20 March 2018, revised 12 June 2018
Accepted for publication 21 June 2018
Published 10 July 2018

Abstract

The magnetotransport properties of the high mobility GaAs/AlGaAs two-dimensional electron gas systems have been examined to determine the influence of the ac current bias on the carrier temperature. The changes in the line shape of Shubnikov–de Haas oscillations in the longitudinal magnetoresistance (ΔR_{xx}) were followed as a function of the ac current bias in the temperature range of $1.6\ \mathrm{K} \leqslant T \leqslant 4.2\ \mathrm{K}$ in order to determine the carrier heating effect due to the ac bias. The lineshape analysis of these oscillations indicates that the carrier temperature of the two-dimensional electron system is linearly proportional to the ac bias current.

Keywords: electron temperature, magnetoresistance, 2D electron system, Shubnikov–de Haas oscillations

(Some figures may appear in colour only in the online journal)

The high mobility GaAs/AlGaAs 2D electron system exhibits lots of fascinating phenomena at low magnetic fields and liquid helium temperatures including, for example, the microwave induced effects [1–30] and a giant magnetoresistance (GMR) effect [15, 22, 31–40]. Studies have shown that a supplementary dc-current can be used to obtain in-situ tunability of the GMR effect at a fixed temperature, and these studies have suggested that, this effect could be responsive to the heating of carriers [22]. To examine the influence of the ac bias current on carrier temperature in this 2D electron systems, we used magnetotransport measurements in the high mobility GaAs/AlGaAs two-dimensional electron gas system (2DES) to follow the lineshape of (Shubnikov–de Haas) SdH oscillations as a function of the ac-bias-current.

Studies of the SdH oscillations in the 2DES plays an important role in the revelation of the quantum mechanical constitution of matter, and they serve to interrogate the properties of charge carriers, such as effective mass and carrier temperature [10, 41–53]. SdH oscillations are observable in the diagonal electrical resistance of electronic systems at weak magnetic fields and low temperatures, and they are responsive to the ratio between the Fermi energy, E_{F}, and the cyclotron energy, $\hbar\omega_{\mathrm{c}}$, as $\omega_{\mathrm{c}} = eB/m^{*}$ is directly proportional to the magnetic field. Here, e (m^{*}) is the electron charge (effective mass). SdH oscillations are periodic in the inverse magnetic field and peaks in the diagonal magnetoresistance R_{xx} occur when Fermi level sweeps through the centers of the Landau levels [54–59] Electron scattering influences the lineshape of SdH

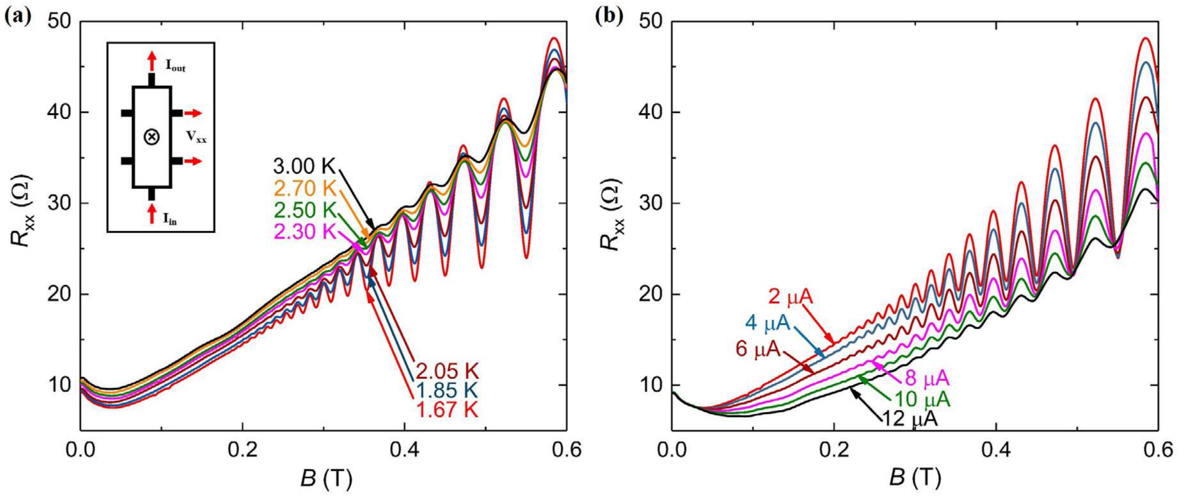

Figure 1. (a) Diagonal resistance R_{xx} with the applied magnetic field at different sample temperatures (ac bias current—2 μA). Inset shows the schematic diagram of the sample. (b) R_{xx} with the applied magnetic field at different bias currents (sample bath temperature equals 1.7 K).

oscillations. Dingle showed that electron scattering sets the effective temperature that is manifested in the lineshape of SdH oscillations [55].

In this study, lock-in based four-terminal magnetoresistance measurements were carried out under a perpendicular magnetic field to investigate the magnetotransport properties of two Hall bar devices, see inset of the figure 1(a), fabricated from GaAs/AlGaAs heterostructures with mobility equal to 6.6×10^6 and 1.1×10^7 cm^2 V^{-1} s^{-1}. GaAs/AlGaAs heterostructures were grown using molecular beam epitaxy (MBE), and the spacer and cap layer thicknesses are 700 Å and 100 Å, respectively, as an electron donor layer, 5 Å thick Si doped (δ—doping) AlGaAs layer with the concentration of 10^{12} cm^{-2} was grown at the top of the spacer. The width of the Hall bar channel is 200 Å, and the distance between potential contacts is 400 Å. Longitudinal voltage (V_{xx}) measurements were taken at different ac current bias over the span ($0 \leqslant I_{ac} \leqslant 12$ μA) at different bath temperatures (1.6 K $\leqslant T_b \leqslant$ 4.2 K), as these temperatures were realized by submerging the sample in pumped liquid helium. The measured voltages were converted into diagonal resistances R_{xx} using Ohms law. The SdH line shape of background subtracted longitudinal magnetoresistance (ΔR_{xx}) was quantitatively analyzed by fitting them with a simplified form of Lifshitz–Kosevich theory [41, 54, 56–59] to determine the elevated temperature of the carriers due to the increment of the current bias; the dependency of the carrier temperature on current bias was obtained.

Figure 1(a) shows the diagonal magnetoresistance at $I_{ac} = 2$ μA, as bath temperature of the sample varied from 1.67 K to 3.00 K. The figure shows that, while the R_{xx} at zero magnetic field is increasing with the sample temperature, the amplitudes of the SdH oscillations are decreasing with the temperature. Figure 1(b) shows the magnetoresistance at 1.67 K, as the ac-bias current I_{ac} varied from 2 μA to 12 μA. Here, R_{xx} corresponding to the magnetic fields below 0.03 T, is hardly influenced by the bias current while it is substantially changing with the magnetic field after 0.03 T. The R_{xx} under 0.03 T is similar in shape to the weak localization effect. [60] In between 0.03–0.07 T, magnetoresistance is decreasing both with the magnetic field and I_{ac}, and at 0.01 T, R_{xx} reduces by 29% when current goes from 2 μA to 12 μA. Even though the magnetic field at which SdH oscillations appear in R_{xx} is shifting with the temperature (figure 1(a)), we do not see a significant change in the starting point of SdH oscillation regime with the current bias.

Both an increase in the temperature and the bias current caused a decrease the amplitude of SdH oscillations, which suggests a carrier heating effect produced by the ac bias. Therefore, to understand and quantify the ac-bias effect, we have examined the lineshape of the SdH oscillations. To examine the amplitudes of SdH oscillations, we have removed the background R_{xx} from the data, and background subtracted diagonal resistances ΔR_{xx} are shown in figure 2. Data were taken for two different samples with two different mobility values, and both of them show similar variation of oscillation amplitudes with the bias current. Upper abscissa axis of the curves in figure 2 indicates the inverse magnetic field divided by the period of the oscillations. It can be clearly see that all the minima are located along consecutive integer numbers, and it illustrates the periodicity of oscillations with the inverse magnetic field.

ΔR_{xx} data were fitted to a simplified formula based on Lifshitz–Kosevich theory to obtain the temperature increment induced by the I_{ac}. Per the Lifshitz–Kosevich theory [56, 57], oscillatory part of the diagonal conductivity in the SdH region can be expressed as a function of magnetic field, temperature, and chemical potential. Also, Ando has derived an expression for the SdH oscillations in diagonal conductivity of 2DES as a result of short-range scattering [58, 59]. Further, he shows that in weak magnetic fields oscillations become nearly sinusoidal, with an exponentially damping with the inverse magnetic field and the effective temperature. Since the measured quantity in the experiment was resistance and measurements were taken at weak magnetic fields, we have used following semi-empirical expression to fit our data [41].

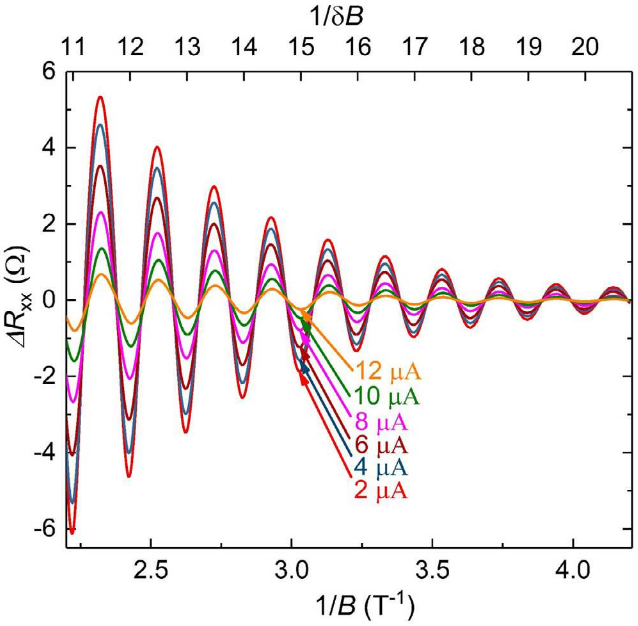

Figure 2. SdH oscillations in ΔR_{xx} are plotted versus the inverse magnetic field $1/B$ at different bias currents at a sample bath temperature of 1.67 K. Upper abscissa axis indicates the $1/\delta B$ where δ is the period of the oscillations.

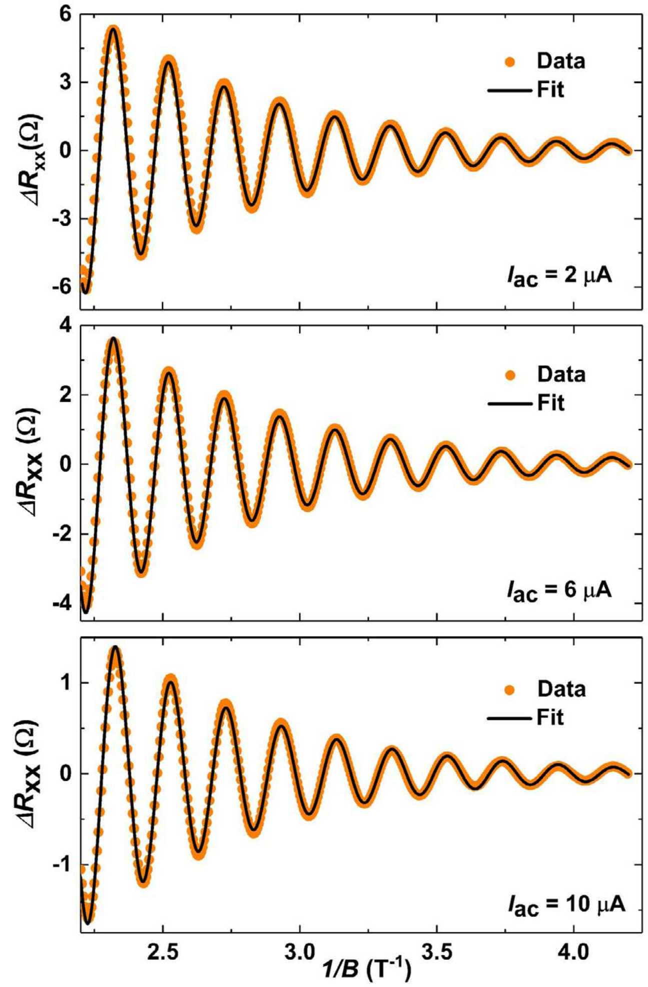

Figure 3. SdH oscillations in ΔR_{xx} with $1/B$ (orange circles) and numerical fits (black solid lines) at the indicated bias currents with the sample bath temperature set at 1.67 K.

$$\Delta R_{xx} = -A\mathrm{e}^{(-\alpha(T_\mathrm{b}+\Delta T)/B)}\cos(2\pi F/B).$$

Where the damping factor $\alpha = (2\pi^2 k_\mathrm{B} m^*/\hbar e)$ and $\Delta T = T_\mathrm{e} - T_\mathrm{b}$. Here m^* is the effective mass of the carriers, T_b is the bath temperature, T_e is the carrier temperature, and B is the magnetic field. Figure 3 shows the experimental data and the numerical fits of ΔR_{xx} at a bath temperature $T = 1.67$ K with different I_ac.

The fit extracted carrier temperatures with the bias current for different bath temperatures are shown in figure 4(a). All the curves converge towards the bath temperature when the ac-bias currents approach zero. According to this analysis, the carrier temperature is linearly increasing with the ac bias current. To clearly illustrate the linear relationship, we have plotted the increment of the carrier temperature with the bias current in the inset to figure 4(b). Curves at different sample temperatures are offset by 0.02 K for the sake of clarity. Figure 4(b) shows the calculated rate of carrier temperature increment with the ac current for both samples at different bath temperatures.

The electron temperature extracted from the amplitudes of SdH oscillations in the GaAs/AlGaAs 2D electron system in low magnetic fields appears to increase linearly with the applied ac bias current at the rate of 4.93 ± 0.04 mK $\mu\mathrm{A}^{-1}$. The carrier temperature in a metallic system under Joule heating depends on both heating, and energy relaxation, which occurs due to both electron–electron scattering and electron–phonon scattering [36, 61–69]. The contribution to the energy relaxation from each mechanism depends also on experimental parameters such as the magnetic field and sample temperature. Since these experiments indicate that the electron temperature is higher than the lattice temperature, the electronic system is apparently in a non-equiibrium state with hot electrons in a lattice that is in thermal equilibrium with the liquid helium bath, i.e. $T_\mathrm{e} > T_\mathrm{b}$ [36, 51, 65].

Below, we estimate the dependence of the electron temperature on the current in order to compare with the results of figure 4. In the absence of an external magnetic field, an applied current bias, I, produces Joule heating as $P = I^2R$, where R is the resistance of the specimen. This Joule heating boosts the electronic energy per unit area, u, as $I^2R = A\Delta u/\tau_\mathrm{e}$, where τ_e is the energy relaxation time, and $A = L \times W$, with L (W) as the length (width) of the Hall bar. From weak localization studies in such specimens, the inelastic length was determined, and from that, we obtained an energy relaxation time, $\tau_\mathrm{e} = 4.75 \times 10^{-9}$ s. The electronic energy is given by $u = \int ED(E)\,f(E,T)\mathrm{d}E$, where $D(E)$ is the 2D electronic density of states, E is the energy, and $f(E,T)$ is the Fermi distribution function. Using the Sommerfeld expansion and neglecting higher order terms $O([k_\mathrm{B}T]^4)$, $u \approx (nE_\mathrm{F}/2) + (n\pi^2(k_\mathrm{B}T)^2/6E_\mathrm{F})$, where n is the electron density, and E_F is the Fermi energy. Thus,

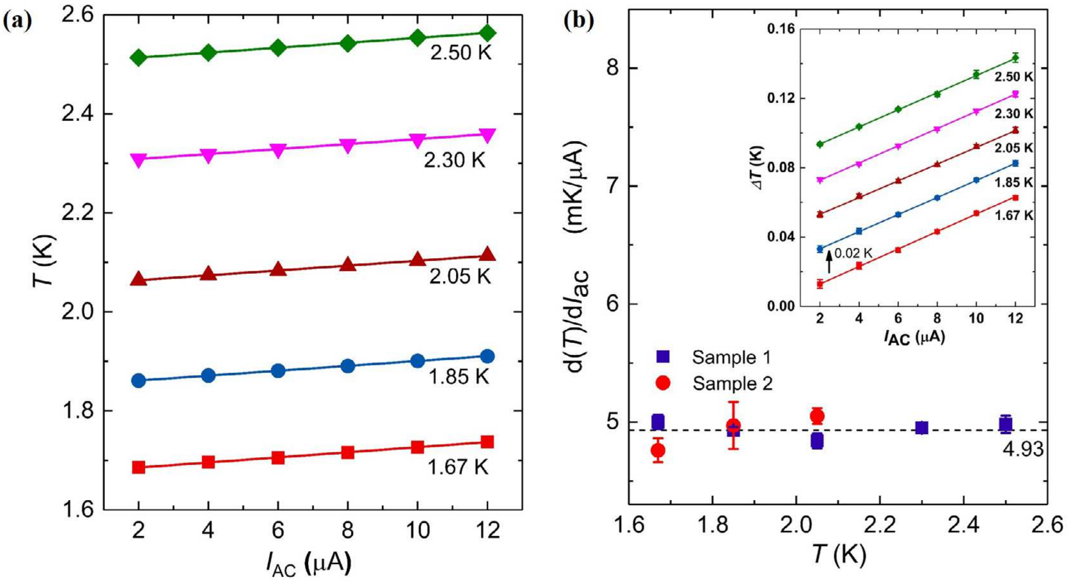

Figure 4. (a) Extracted carrier temperatures from the numerical fits with the bias current at different sample temperatures. (b) The rate of increment of the carrier temperature with the bias current at different sample temperatures for two different AlGaAs samples with mobility equal to 6.6×10^6 cm^2 V^{-1} s^{-1} (blue squares) and 1.1×10^7 cm^2 V^{-1} s^{-1} (red circles). The inset shows the calculated Increment of the carrier temperatures with the bias current at different sample temperatures for sample with 6.6×10^6 cm^2 V^{-1} s^{-1} mobility. Data at different sample temperatures are offset by 0.02 K for the clarity.

the increase in the electron temperature, ΔT can be estimated from $I^2R \approx A\pi^2 k_B^2 n(\Delta T)^2/6E_F\tau_e$. The effective mass of the electron and fermi energy of the system are 0.064 and 9.2 meV respectively. Using standard Drude relations, the relationship between the temperature increment and bias current in the absence of a magnetic field becomes $\Delta T \approx \sqrt{6\hbar^2\tau_e/\pi k_B^2 e^2 W^2 n\tau_m}\, I$. Where τ_m is the momentum relaxation time, and it is equal to 3.64×10^{-10} s.

These relations suggest a linear variation in the electron temperature with the current, as observed, and they indicate $\mathrm{d}T/\mathrm{d}I \approx 24$ mK μA^{-1} in the absence of a magnetic field, which is compared here with the observed value $\mathrm{d}T/\mathrm{d}I_{ac} = 4.93$ mK μA^{-1} obtained from this study of the low magnetic field SdH effect. The study of the faster than expected rise in the electron temperature with the current will constitute a topic for future investigation.

Acknowledgments

Research support has been provided by the NSF under ECCS-1710302. Magnetotransport studies at Georgia State University have been funded by US Department of Energy, Office of Basic Energy Sciences, Material Sciences and Engineering division under Grant No. DE-SC0001762. 2D material study has been funded by Army Research Office under W911NF- 14-2-0076 and W911NF-15-1-0433.

ORCID iDs

C Rasadi Munasinghe https://orcid.org/0000-0002-2909-0201

References

[1] Mani R G, Smet J H, Von Klitzing K, Narayanamurti V, Johnson W B and Umansky V 2002 *Nature* **420** 646
Mani R G, Smet J H, Von Klitzing K, Narayanamurti V, Johnson W B and Umansky V 2002 *Phys. Rev. Lett.* **92** 146801
Mani R G, Smet J H, Von Klitzing K, Narayanamurti V, Johnson W B and Umansky V 2002 *Phys. Rev.* B **69** 193304

[2] Zudov M A, Du R R, Pfeiffer L N and West K W 2003 *Phys. Rev. Lett.* **90** 046807

[3] Mani R G, Narayanamurti V, Von Klitzing K, Smet J H, Johnson W B and Umansky V 2004 *Phys. Rev.* B **70** 155310
Mani R G, Narayanamurti V, Von Klitzing K, Smet J H, Johnson W B and Umansky V 2004 *Phys. Rev.* B **69** 161306

[4] Kovalev A E, Zvyagin S A, Bowers C R, Reno J L and Simmons J A 2004 *Solid State Commun.* **130** 379

[5] Simovic B, Ellenberger C, Ensslin K, Tranitz H P and Wegscheider W 2005 *Phys. Rev.* B **71** 233303

[6] Mani R G 2004 *Physica* E **22** 1
Mani R G 2004 *Physica* E **25** 189
Mani R G 2005 *Phys. Rev.* B **72** 075327
Mani R G 2008 *Physica* E **40** 1178
Mani R G 2008 *Appl. Phys. Lett.* **92** 102107
Mani R G 2007 *Appl. Phys. Lett.* **91** 132103

[7] Wiedmann S *et al* 2008 *Phys. Rev.* B **78** 121301
Wiedmann S *et al* 2011 *Phys. Rev.* B **16** 165303

[8] Mani R G *et al* 2009 *Phys. Rev.* B **79** 205320
Mani R G *et al* 2010 *Phys. Rev.* B **81** 125320

[9] Fedorych O M, Potemski M, Studentikin S A, Gupta J A, Wasilewski Z R and Dmitriev I 2010 *Phys. Rev.* B **81** 201302

[10] Ramanayaka A N, Mani R G and Wegscheider W 2011 *Phys. Rev.* B **83** 165303

[11] Dai Y H, Stone K, Knez I, Zhang C, Du R R, Yang C L, Pfeiffer L N and West K W 2011 *Phys. Rev.* B **84** 241303

[12] Mani R G, Ramanayaka A N and Wegscheider W 2011 *Phys. Rev.* B **84** 085308
Ramanayaka A N, Mani R G, Inarrea J and Wegscheider W 2012 *Phys. Rev.* B **85** 205315

[13] Mani R G *et al* 2013 *Phys. Rev.* B **87** 245308
Mani R G *et al* 2013 *Sci. Rep.* **3** 2747
Mani R G *et al* 2012 *Nat. Commun.* **3** 996

[14] Ye T *et al* 2013 *Appl. Phys. Lett.* **103** 192106
Ye T *et al* 2013 *Appl. Phys. Lett.* **102** 242113
Ye T *et al* 2014 *Phys. Rev.* B **89** 155307
Ye T *et al* 2014 *Appl. Phys. Lett.* **105** 191609
Ye T *et al* 2015 *Sci. Rep.* **5** 14880
Ye T *et al* 2016 *Phys. Rev.* B **94** 035305

[15] Mani R G, Kriisa A K and Wegscheider W 2013 *Sci. Rep.* **3** 3478

[16] Liu H-C *et al* 2015 *J. Appl. Phys.* **117** 064306

[17] Kvon Z D *et al* 2013 *JETP Lett.* **97** 41

[18] Levin A D, Momtaz Z S, Guzev G M, Raichev O E and Bakarov A K 2015 *Phys. Rev. Lett.* **115** 206801

[19] Chepelianskii A D, Watanabe M, Nasyedkin K, Kono K and Konstantinov D 2015 *Nat. Commun.* **6** 7210

[20] Mani R G 2016 *Appl. Phys. Lett.* **108** 033507
Mani R G 1993 *Z. Phys.* B **92** 335

[21] Iñarrea J, Mani R G and Wegscheider W 2010 *Phys. Rev.* B **82** 205321

[22] Wang Z *et al* 2016 *Sci. Rep.* **6** 38516

[23] Samaraweera R L *et al* 2017 *Sci. Rep.* **7** 5074

[24] Gunawardana B *et al* 2017 *Phys. Rev.* B **95** 195304

[25] Durst A C, Sachdev S, Read N and Girvin S M 2003 *Phys. Rev. Lett.* **91** 086803

[26] Iñarrea J and Platero G 2005 *Phys. Rev. Lett.* **94** 016806
Iñarrea J and Platero G 2006 *Appl. Phys. Lett.* **89** 172114
Iñarrea J and Platero G 2011 *Phys. Rev.* B **76** 073311

[27] Ryzhii V and Suris R 2003 *J. Phys.: Condens. Matter* **15** 6855

[28] Lei X L and Liu S Y 2003 *Phys. Rev. Lett.* **91** 226805
Lei X L and Liu S Y 2006 *Appl. Phys. Lett.* **89** 182117
Lei X L and Liu S Y 2012 *Phys. Rev.* B **86** 205303
Lei X L and Liu S Y 2014 *J. Appl. Phys.* **115** 233711

[29] Iñarrea J 2011 *Appl. Phys. Lett.* **99** 232115
Iñarrea J 2013 *J. Appl. Phys.* **113** 183717
Iñarrea J 2016 *Europhys. Lett.* **113** 57004

[30] Zhirov O V, Chepelianskii A D and Shepelyansky D L 2013 *Phys. Rev.* B **88** 035410

[31] Girvin S M, Jonson M and Lee P A 1982 *Phys. Rev.* B **26** 1651

[32] Houghton A, Senna J R and Ying S C 1982 *Phys. Rev.* B **25** 2196

[33] Mani R G, Von Klitzing K and Ploog K 1993 *Phys. Rev.* B **48** 4571
Mani R G, Von Klitzing K and Ploog K 1992 *Phys. Rev.* B **15** 9877–80

[34] Mirlin A D, Polyakov D G, Evers F and Wolfle P 2001 *Phys. Rev. Lett.* **87** 126805

[35] Li L, Proskuryakov Y Y, Savchenko A K, Linfield E H and Ritchie D A 2003 *Phys. Rev. Lett.* **90** 076802

[36] Bykov A A, Zhang J Q, Vitkalov S, Kalagin A K and Bakarov A 2007 *Phys. Rev. Lett.* **99** 116801

[37] Inarrea J 2009 *Phys. Rev.* B **80** 193302
Inarrea J 2014 *Europhys. Lett.* **106** 47005

[38] Bockhorn L *et al* 2011 *Phys. Rev.* B **83** 113301
Bockhorn L *et al* 2014 *Phys. Rev.* B **90** 165434

[39] Choi K K, Tsui D C and Alavi K 1987 *Phys. Rev.* B **15** 7751

[40] Inarrea J, Bockhorn L and Haug R J 2016 *Europhys. Lett.* **115** 17005

[41] Mani R G and Anderson J R 1988 *Phys. Rev.* B **37** 4299

[42] Cao H *et al* 2012 *Phys. Rev. Lett.* **108** 216803

[43] Tan Z, Tan C, Ma L, Liu G T, Lu L and Yang C L 2011 *Phys. Rev.* B **84** 115429

[44] Blom F A F *et al* 1990 *Surf. Sci.* **229** 70–2

[45] Zou K, Hong X and Zhu J 2011 *Phys. Rev.* B **84** 085408

[46] Kulbachinskii V A *et al* 2016 *J. Phys.: Conf. Ser.* **568** 052013

[47] Fluegel B, Kini R N, Ptak A J, Beaton D, Alberi K and Mascarenhas A 2011 *Appl. Phys. Lett.* **99** 162108

[48] Diaz-Paniagua C *et al* 1999 *Solid State Commun.* **109** 785–90

[49] Fallahazad B *et al* 2016 *Phys. Rev. Lett.* **116** 086601

[50] Shrestha K, Marinova V, Lorenz B and Chu P C W 2014 *Phys. Rev.* B **90** 241111

[51] Lei X L and Liu S Y 2005 *Phys. Rev.* B **72** 075345

[52] Asmar N G *et al* 1996 *Appl. Phys. Lett.* **68** 829

[53] Xu W and Zhang C 1997 *Phys. Rev.* B **55** 5259

[54] Shoenberg D 1988 *J. Phys. F: Met. Phys.* **18** 49

[55] Dingle R B 1952 *Proc. R. Soc.* A **211** 500

[56] Lifshitz I M 1957 *J. Exp. Theor. Phys.* **5** 6–1227

[57] Lifshitz I M and Kosevich L M 1958 *J. Exp. Theor. Phys.* **6** 67

[58] Ando T 1974 *J. Phys. Soc. Japan* **37** 1233

[59] Ando T, Fowler A B and Stern F 1982 *Rev. Mod. Phys.* **54** 437

[60] Bergmann G 1984 *Phys. Rep.* **107** 1

[61] Taubert D *et al* 2011 *Phys. Rev.* B **83** 235404

[62] Zhang J Q, Vitkalov S and Bykov A A 2009 *Phys. Rev.* B **80** 045310

[63] Sakaki H *et al* 1984 *Surf. Sci.* **142** 306–13

[64] Potts A *et al* 1990 *J. Phys.: Condens. Matter* **2** 1817

[65] Viljas J K and Heikkila T T 2010 *Phys. Rev.* B **81** 245404

[66] Trushin M and Schliemann J 2007 *Phys. Rev. Lett.* **99** 216602

[67] Graf M J, Yip S-K, Sauls J A and Rainer D 1996 *Phys. Rev.* B **53** 15147

[68] Pinsolle E, Rousseau A, Lupien C and Reulet B 2016 *Phys. Rev. Lett.* **116** 236601

[69] Gurevich Yu G, Logvinov G N, Carballo-Sanchez A F, Drogobitskiy Yu V and Salazar J L 2002 *J. Appl. Phys.* **91** 18