Эффекты квантового туннелирования и классического протекания в режиме квантового эффекта Холла в гетероструктурах на основе HgTe с широкой квантовой ямой

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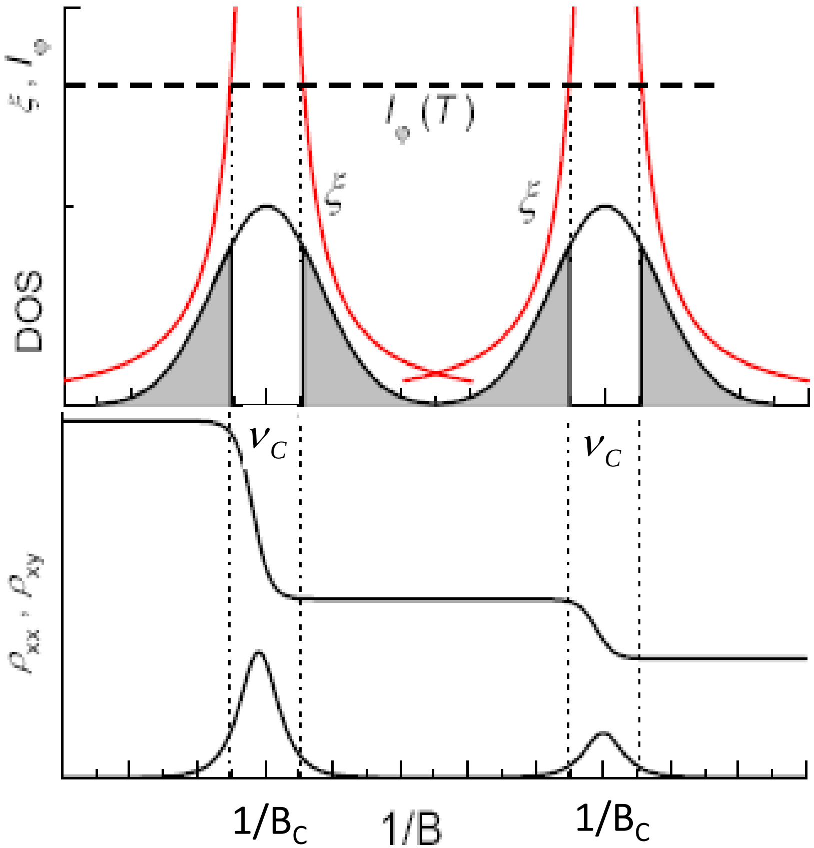
Conductivity in quantum Hall effect regime
Scaling hypothesis

Laughlin Phys.Rev.B 1981

Halperin Phys.Rev.B 1982



Schematic representation of the scaling behavior in the quantum Hall regime. The width of the extended states, and thereby the shape of the ρ_{ij} resistance features is determined by the ratio $l\varphi(T)/\xi$.

Resistivity tensor depends on two length scales:

- Localization length ξ.

It diverges at B_c *as* $\xi \sim |B - B_C|^{-\gamma} \sim |\nu - \nu_C|^{-\gamma}$

γ - localization length exponent; $\nu = \dfrac{nh}{eB}$

- Sample size L is determined by the dephasing length l_φ: $L \propto l_\varphi \sim T^{-p/2}$ p – dephasing length exponent.

Scaling relation for $L>l_\varphi$:

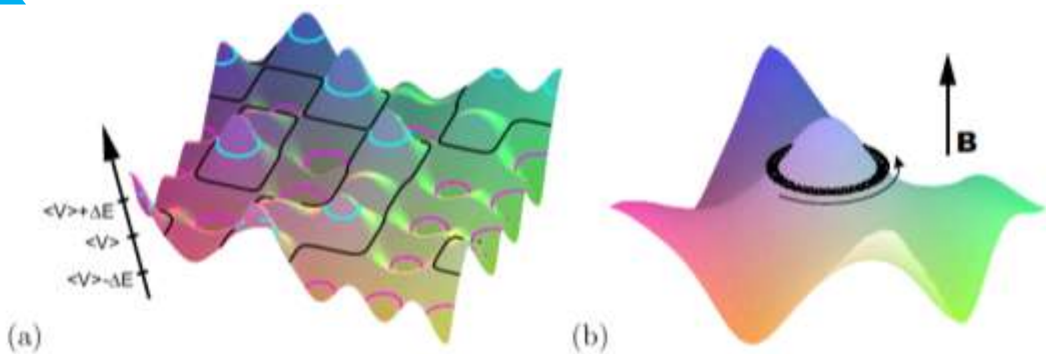
$$\rho_{ij} = g\left((L/l_\varphi)^{1/\gamma}\right) = g\left(T^{-p/2\gamma}(B - B_c)\right)$$

κ=p/2γ

*A.M.M. Pruisken. Nucl. Phys. B, 1984. v. **235** [FS 11] pp. 277-298.*

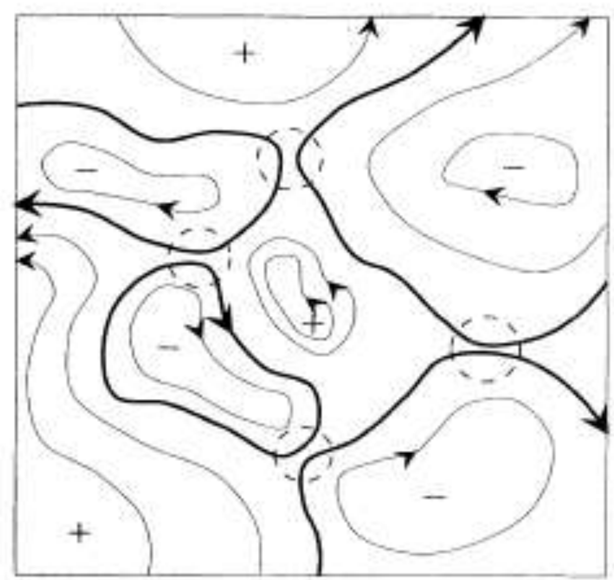
Percolation picture

γ =4/3 [Trugman Phys.Rev.B 1983]



The illustration (a) of a slowly varying random potential V with equipotential lines at $\langle V \rangle$ и $\langle V \rangle \pm \Delta E$, which allows (b) in strong magnetic field to separate the electron motion (black orbit) into cyclotron motion and motion of guiding center of the orbit along equipotentials .

γ=7/3 ~2.3



The equipotential lines of smooth random potential. The thick lines correspond to the links in the network model. The circles enclose the saddle points.

B. Huckestein, Rev. Mod. Phys. **67**, 367 (1995).

[Chalker, Coddington J.Phys.C 1988]

Variable-range hopping conductivity

$$R(T) = R_0 \exp(T_0 / T)^n$$

Mott's law [Mott 1968]

$$n = 1/(d+1)$$

$$R(T) = R_0 \exp(T_0 / T)^{1/3}$$

For 2D DOS - constant

$$g(E) = \frac{2}{\pi} \frac{\varepsilon^2}{e^4} \left| E - E_F \right|$$

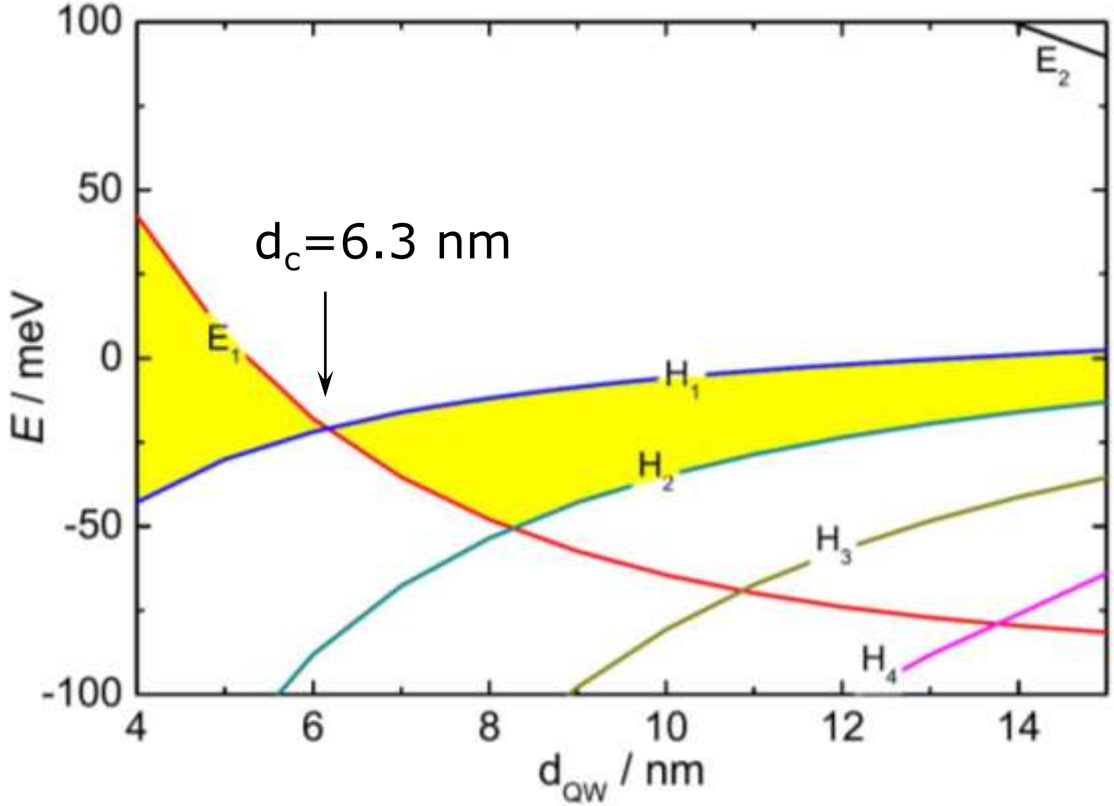
For 2D DOS with Coulomb gap [Efros Shklovskii 1975, Polyakov Shklovskii 1993]

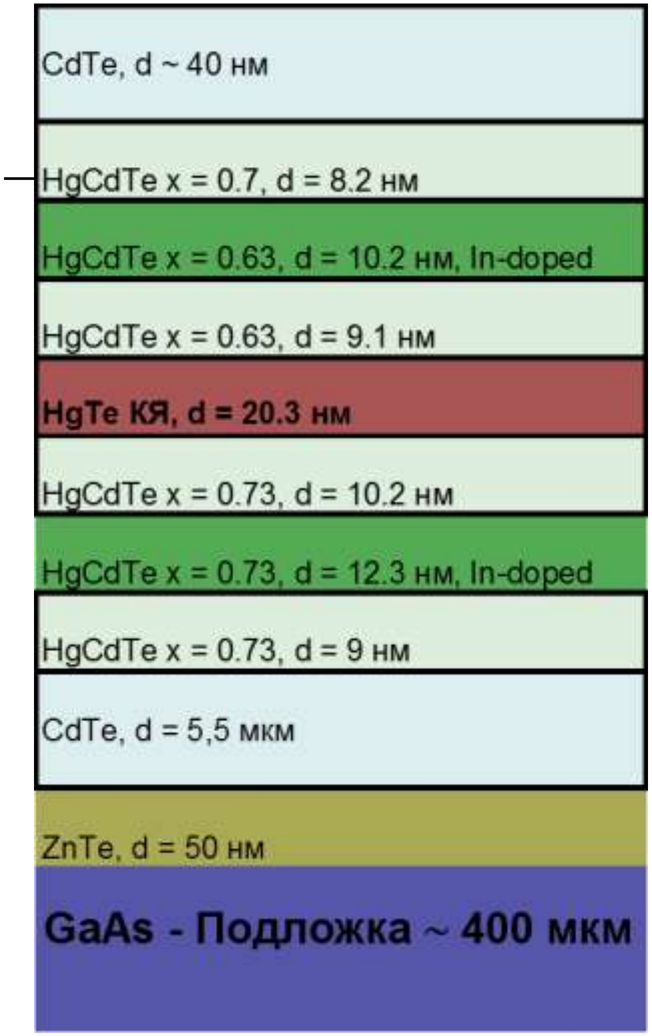
$$\sigma_{xx}(T) = \sigma_0 \exp\left[-(T_0 / T)^{1/2} \right]$$

$$T_0(\nu) = C \frac{1}{k} \frac{e^2}{\varepsilon \xi(\nu)} \qquad \sigma_0 \sim 1/T$$

HgTe/HgCdTe

[M. Koenig…JPSJpn 77 (2008) 031007]





n=1.5*10^{15} м^{-2} m=(0.022÷0.026)m_0

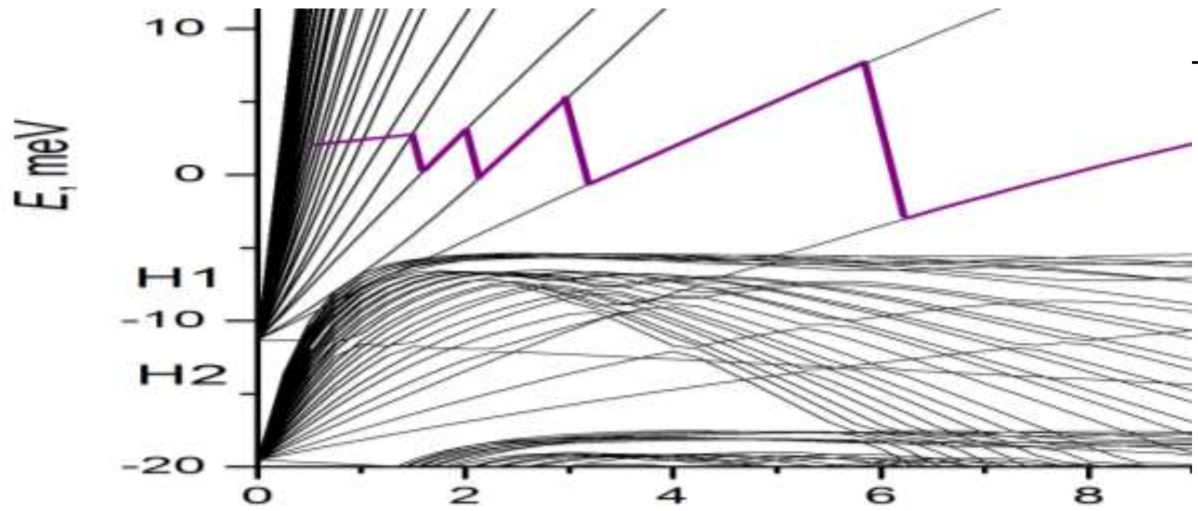
μ=2,2*10^5 $\text{см}^2/\text{Вс}$ g≈50

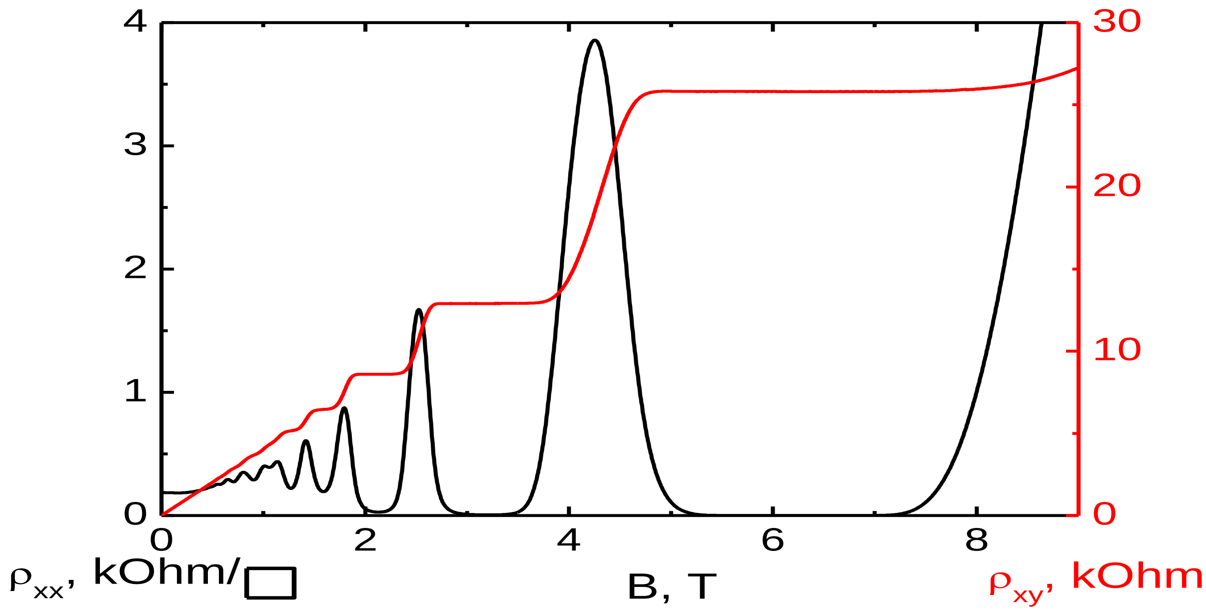
Z. D. Kvon, et al, Low Temp. Phys. **35**, 6 (2009)

Yakunin et al. Physica E 2010

Longitudinal and Hall components of magnetoresistivity tensor and the motion of Fermi level along the Landau levels

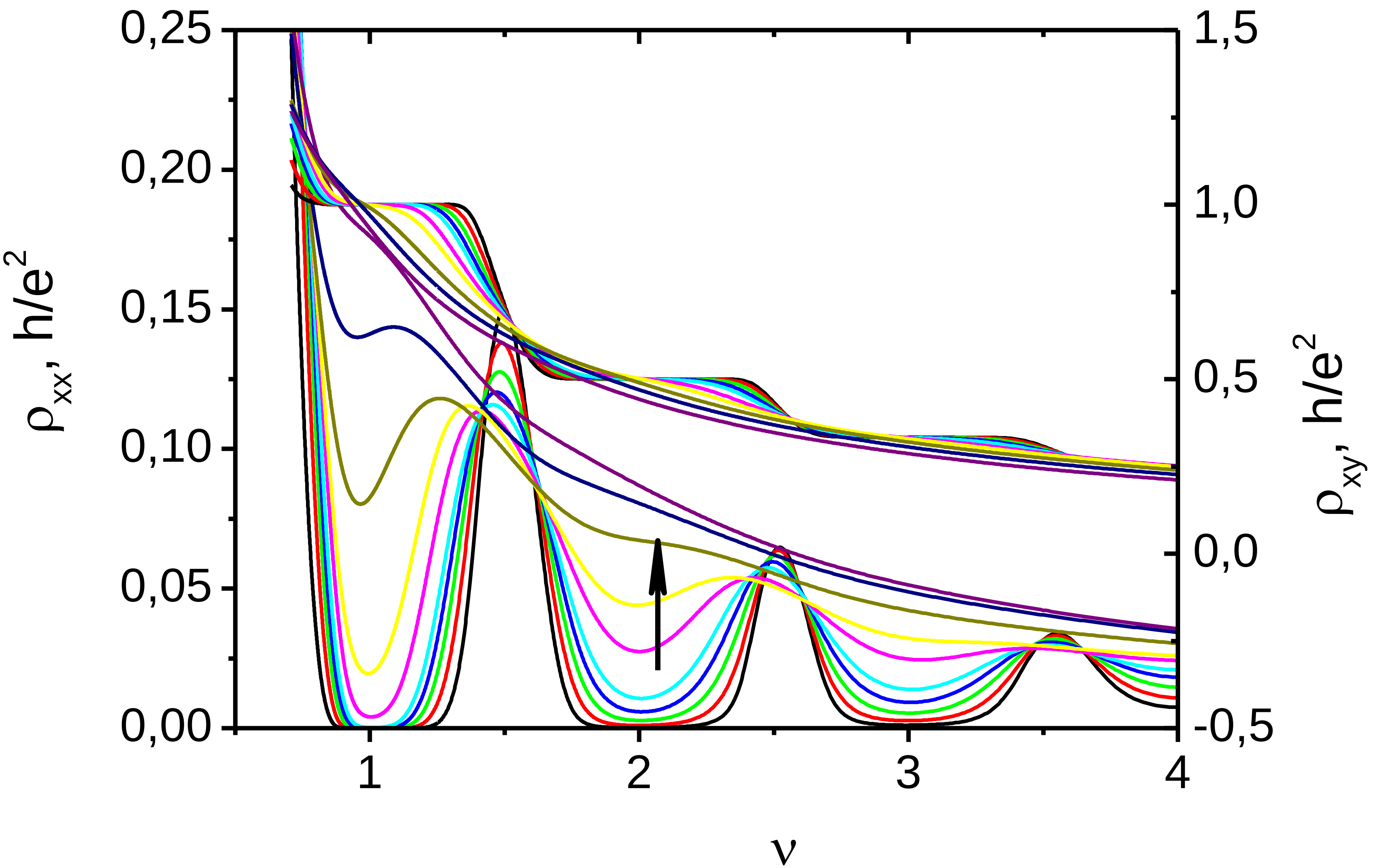
Calculated by E.Novik (A.Astakhova)





Analysis of conductivity in the plateau-plateau transition region

Dependences $\rho_{xx}(\nu)$ and $\rho_{xy}(\nu)$ in a perpendicular magnetic field at fixed T=(2-50)K. Arrow indicates the temperature incrising.



Definition of temperature critical index (critical index of delocalized state band) κ

! $$\left.\frac{d\rho_{xy}}{dB}\right|_{\max} \sim T^{-\kappa}$$

$$\Delta B = \left| B\Big|_{\frac{d\rho_{xx}}{dB}|\max} - B\Big|_{\frac{d\rho_{xx}}{dB}|\min} \right| \sim T^{\kappa}$$

! $$\sigma_{xx} = \frac{s}{1+s^2} \qquad \sigma_{xy} = i - \frac{s^2}{1+s^2}$$

i – plateau number

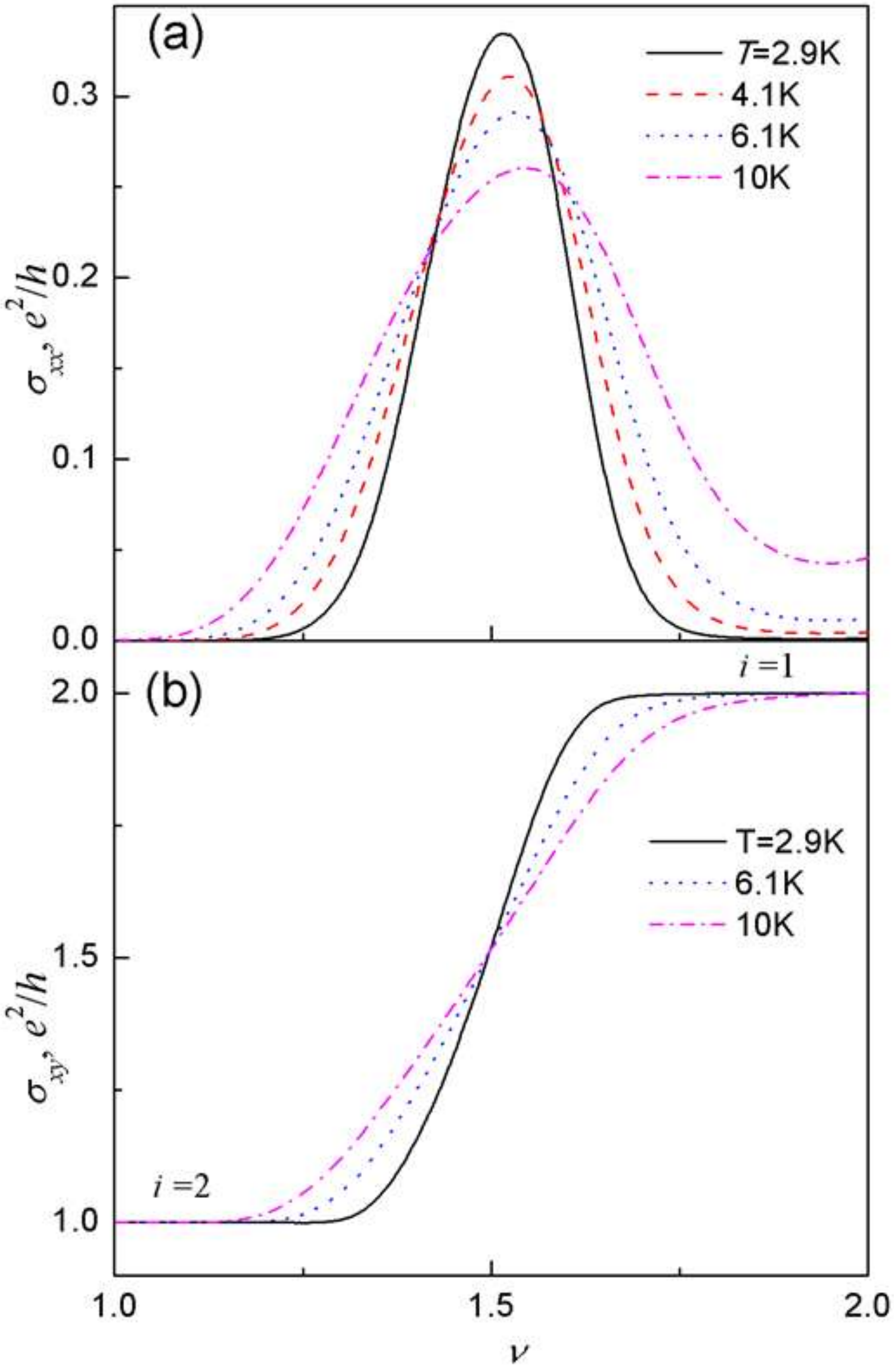
s – scattering parameter $0 \le s \le \infty$ $\quad s(\nu_c) = 1 \quad s \sim \dfrac{R}{T}$

$$s(\nu) = \exp\left(-\frac{\Delta\nu}{\nu_o(T)}\right) \qquad \nu_0(T) \sim T^{-\kappa}$$

R – quantum percolation reflection coefficient

T – quantum percolation transmission coefficient

P. T. Coleridge, Phys. Rev. B **60**, 4493 (1999).



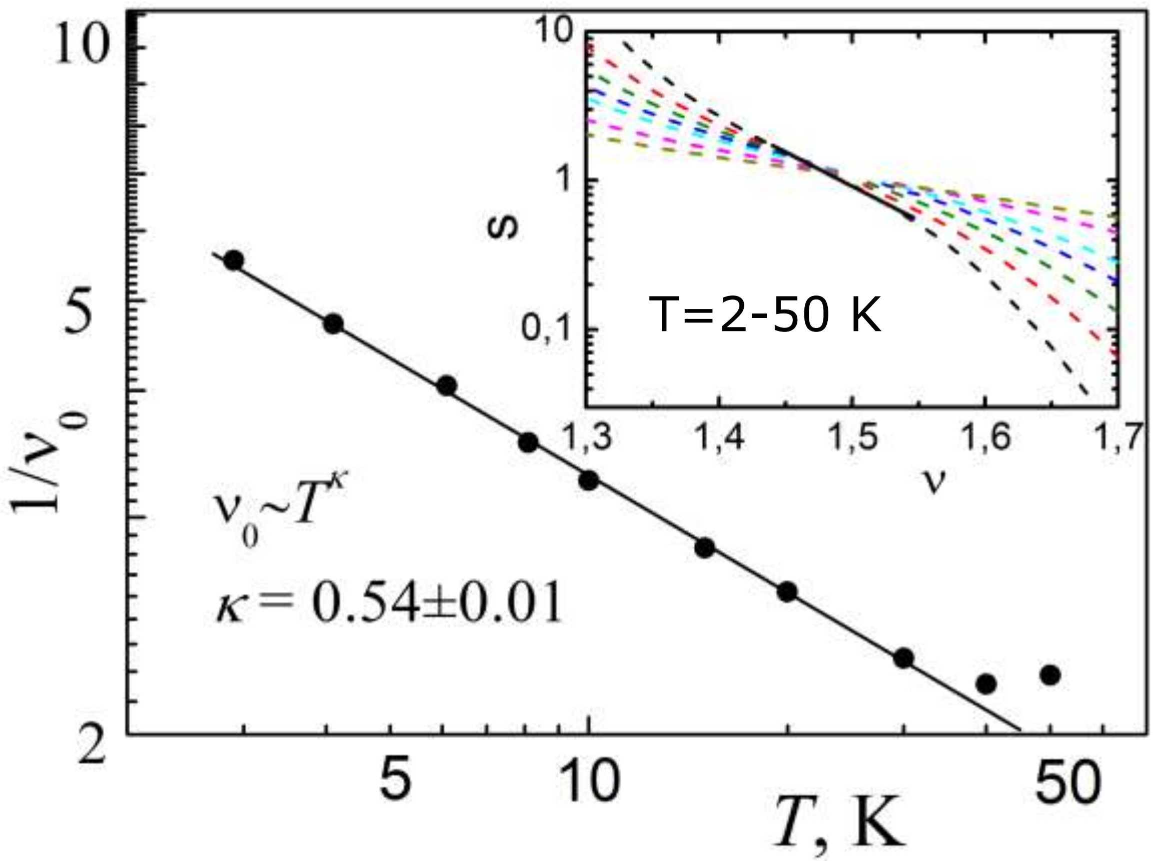
Dependences $\sigma_{xx}(\nu)$ and $\sigma_{xy}(\nu)$ in a perpendicular magnetic field at fixed T for 1→2 plateau-plateau transition.

The inverse bandwidth of delocalized states $1/\nu_0$ as a function of temperature T for the $1 \rightarrow 2$ transition on the log–log scale. Insert: Parameter s (calculated from σ_{xx}) as a function of the filling factor ν (dashed lines) in a semi-logarithmic scale. Solid line shows the segment where the ν_0 was defined.

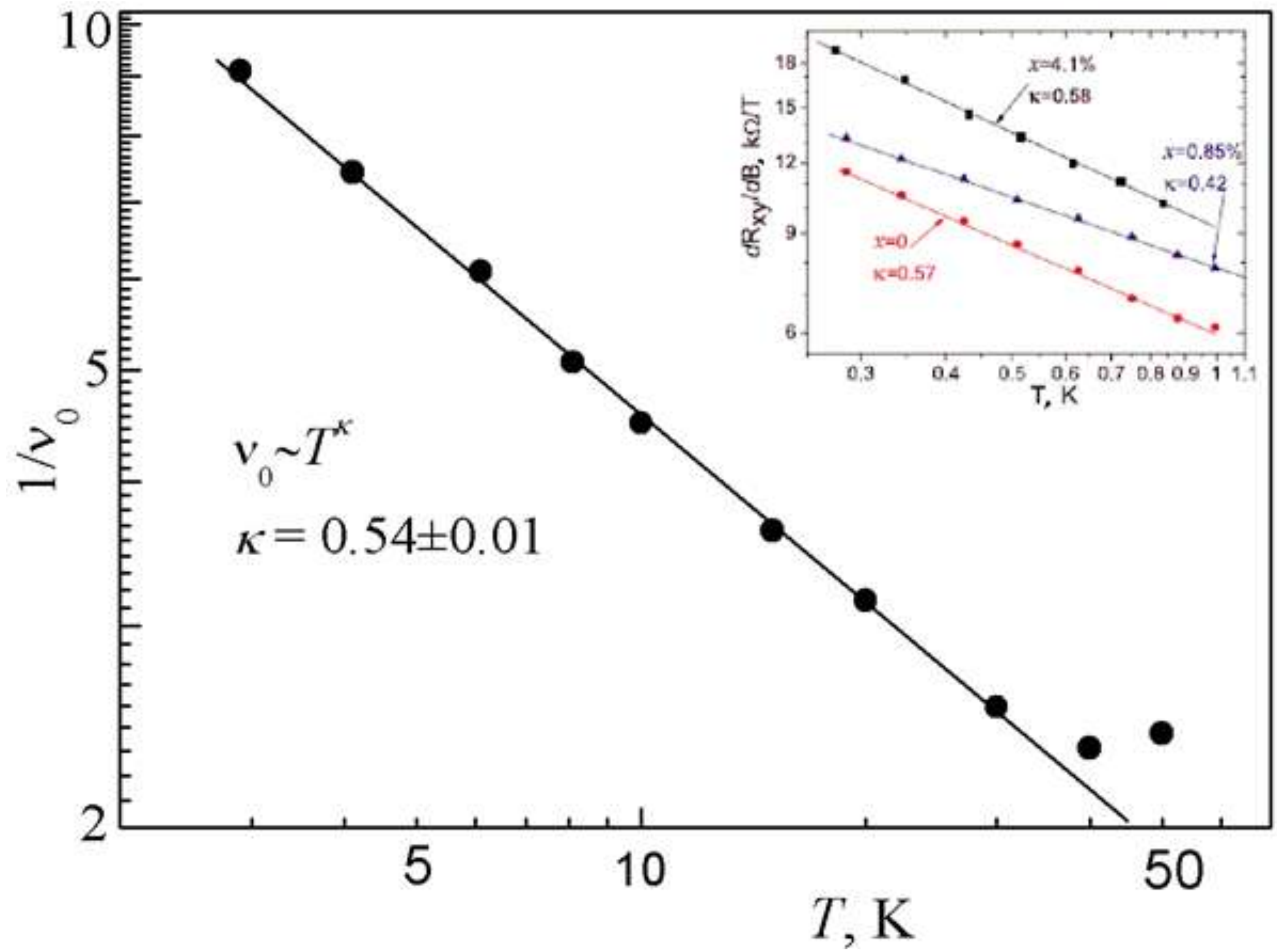
$$\sigma_{xx} = \frac{s}{1+s^2}$$

$$s(\nu) = \exp\left(-\frac{\Delta\nu}{\nu_o(T)}\right)$$

$$\nu_0(T) \sim T^{-\kappa}$$



Dependence of inverse effective width of delocalized state band ν_0 on temperature T for 1→2 transition



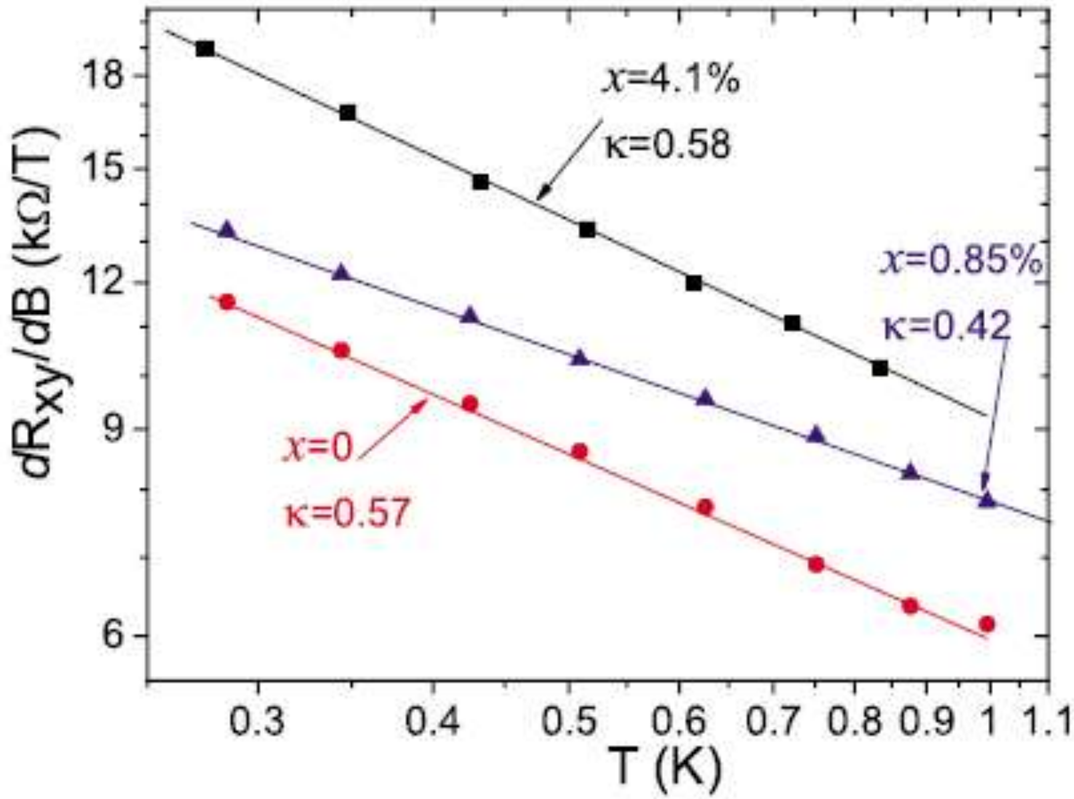
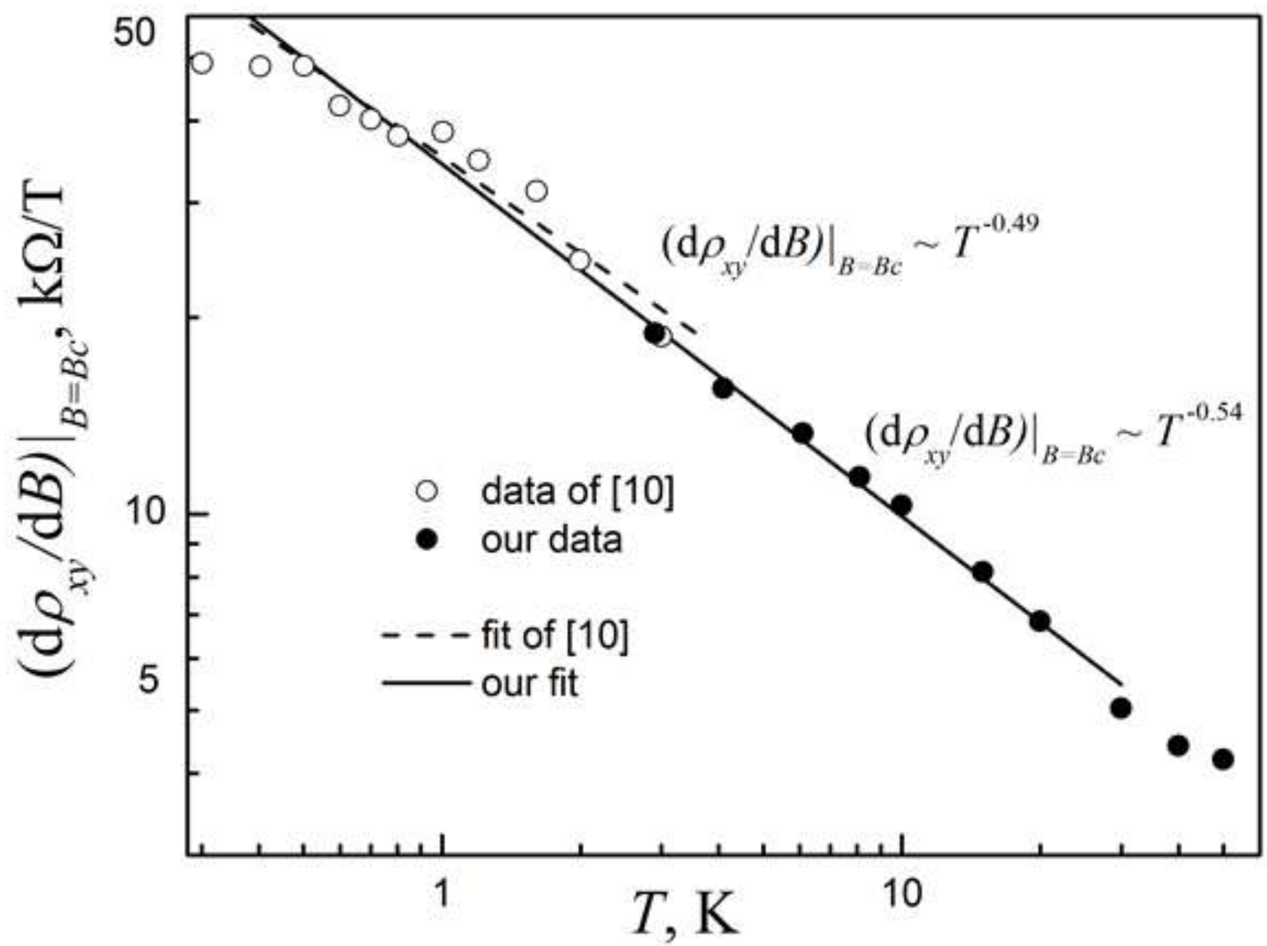


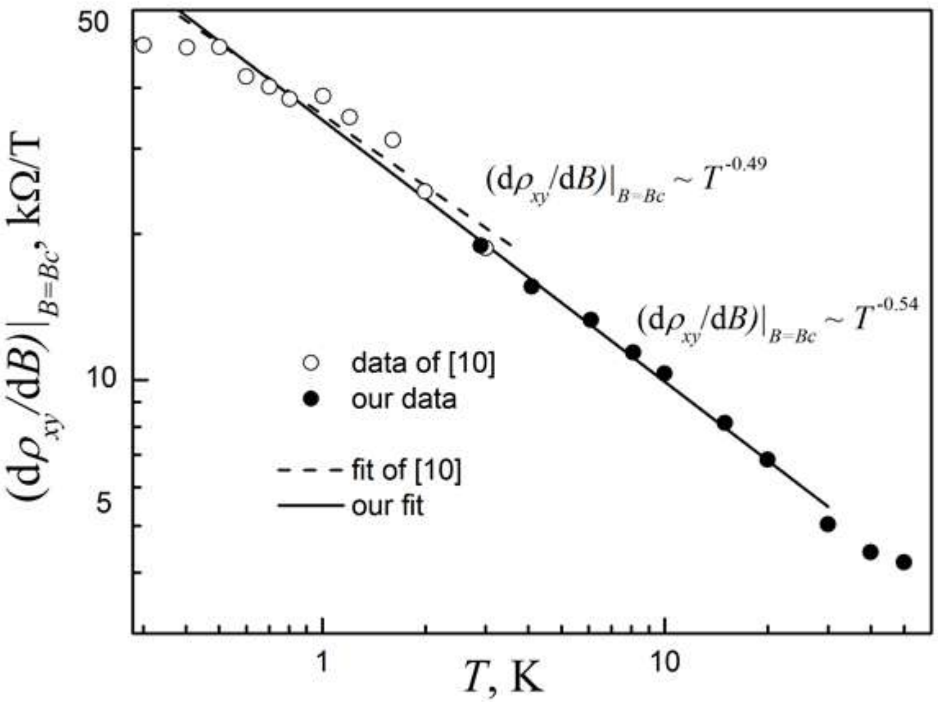
FIG. 2 (color online). $(dR_{xy}/dB)|_{B=B_c}$ vs T for the 4-3 transition. From down to up, $x = 0, 0.85\%, 4.1\%$, respectively. Data of different x has been shifted vertically in a log-log scale for a clear comparison. Scaling exponents κ are obtained from linear fits.

Wang Li et al, Phys.Rev.Lett. 2005

Dependence of divergence of Hall magnetoresistivity $(d\rho_{xy}/dB)|_{B=Bc}$ on temperature T in double logarithmic scale for 1→2 transition.



[10] E.B. Olshanetsky, S. Sassine, Z.D. Kvon, N.N. Mikhailov, S.A. Dvoretsky, J.C. Portal, A.L. Aseev, Письма в ЖЭТФ, 84, 661 (2006); З.Д. Квон, Е.Б. Ольшанецкий, Н.Н. Михайлов, Д.А. Козлов, ФНТ 35, 10 (2009).



d_{QW} = 5.9 nm

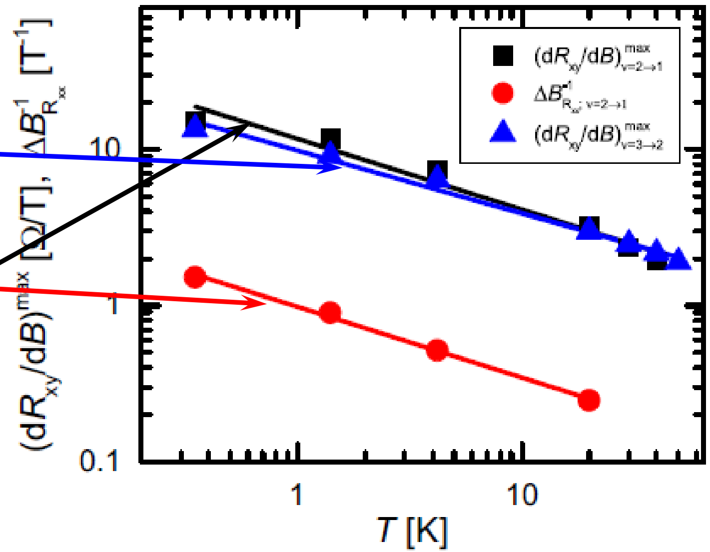
$n = 4.59 \times 10^{11}$ cm^{-2}

μ = 67 800 cm^2/V s

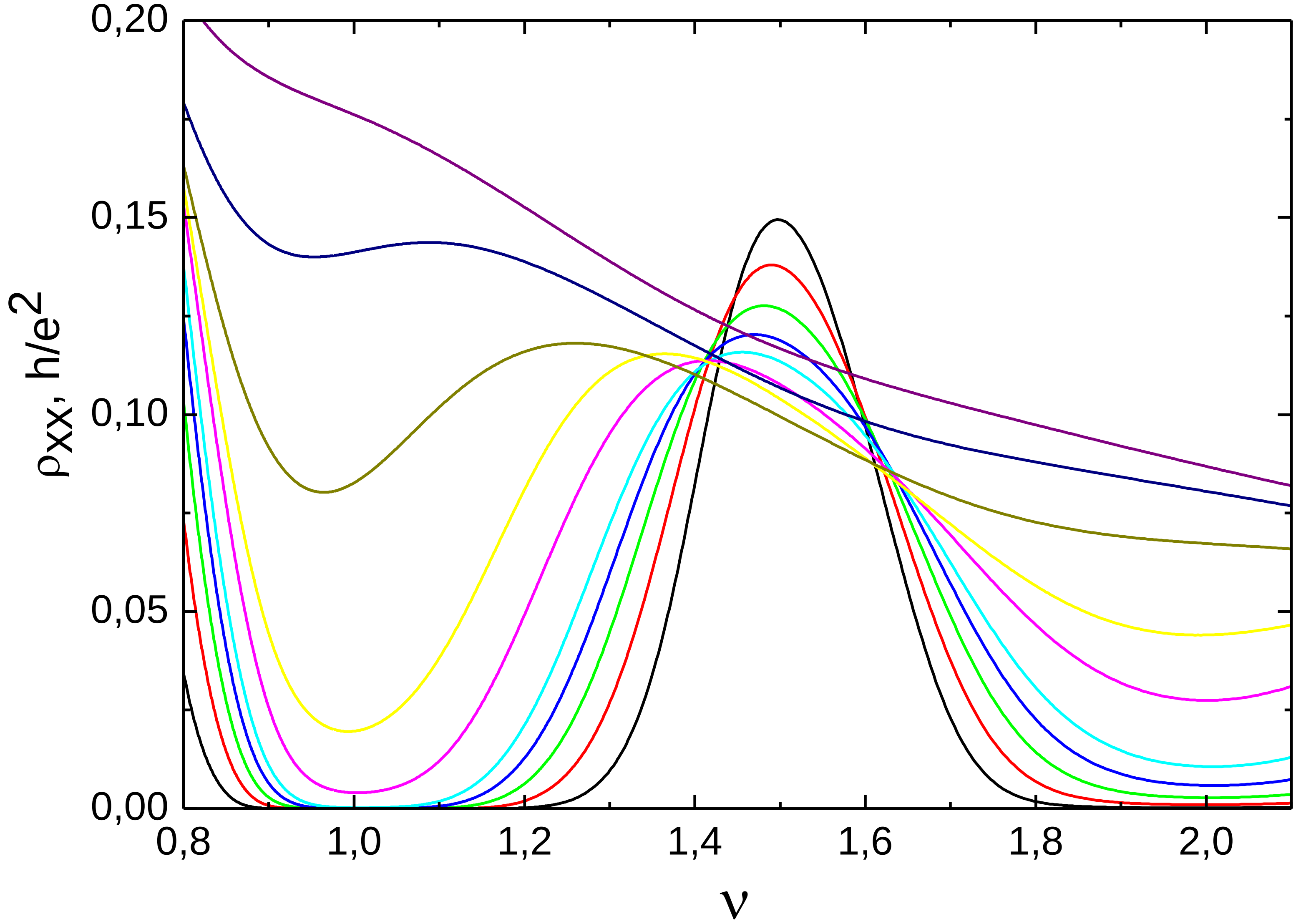
T. Khouri, et al, PHYS REV B **93**, 125308 (2016)

$\kappa = 0.40 \pm 0.02$

$\kappa = 0.45 \pm 0.04$

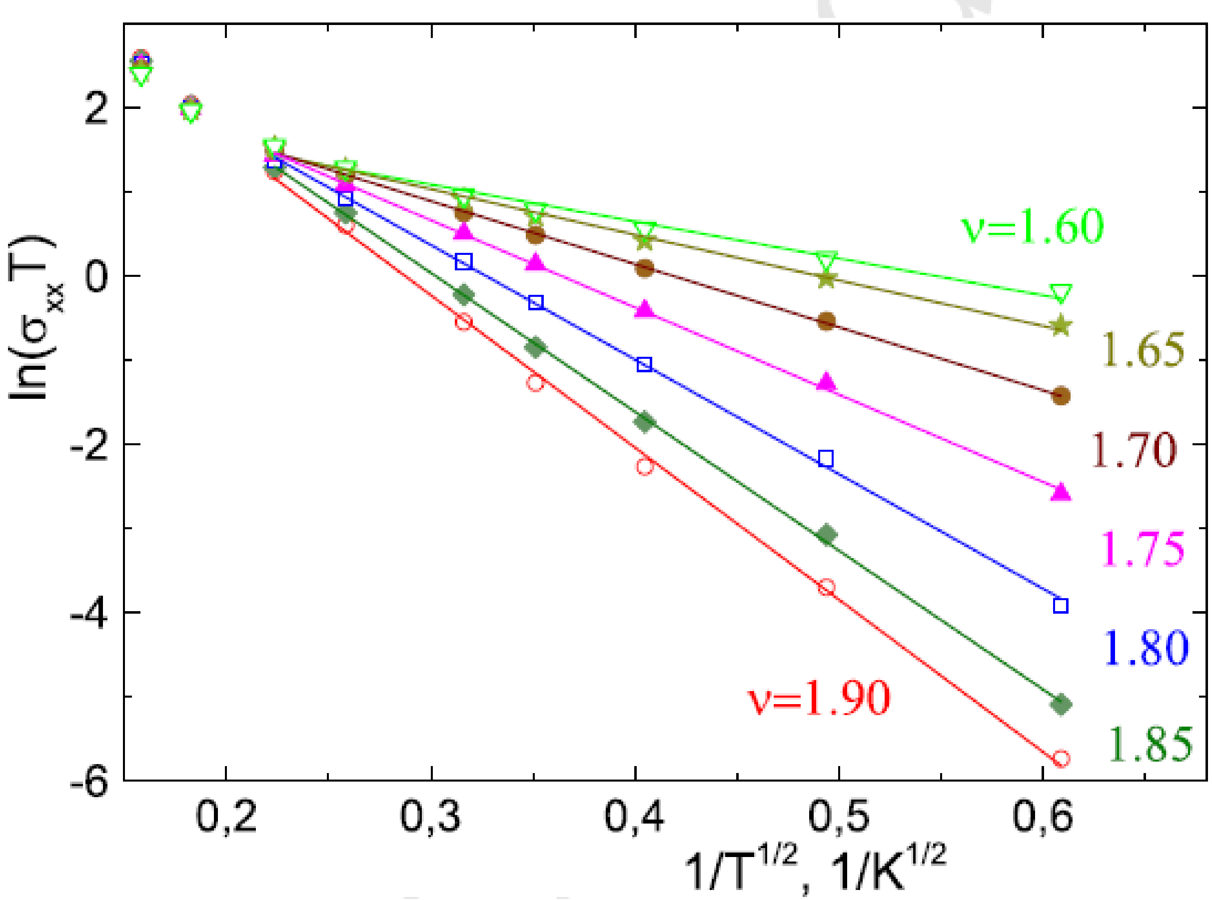


Analysis of conductivity in the plateau region

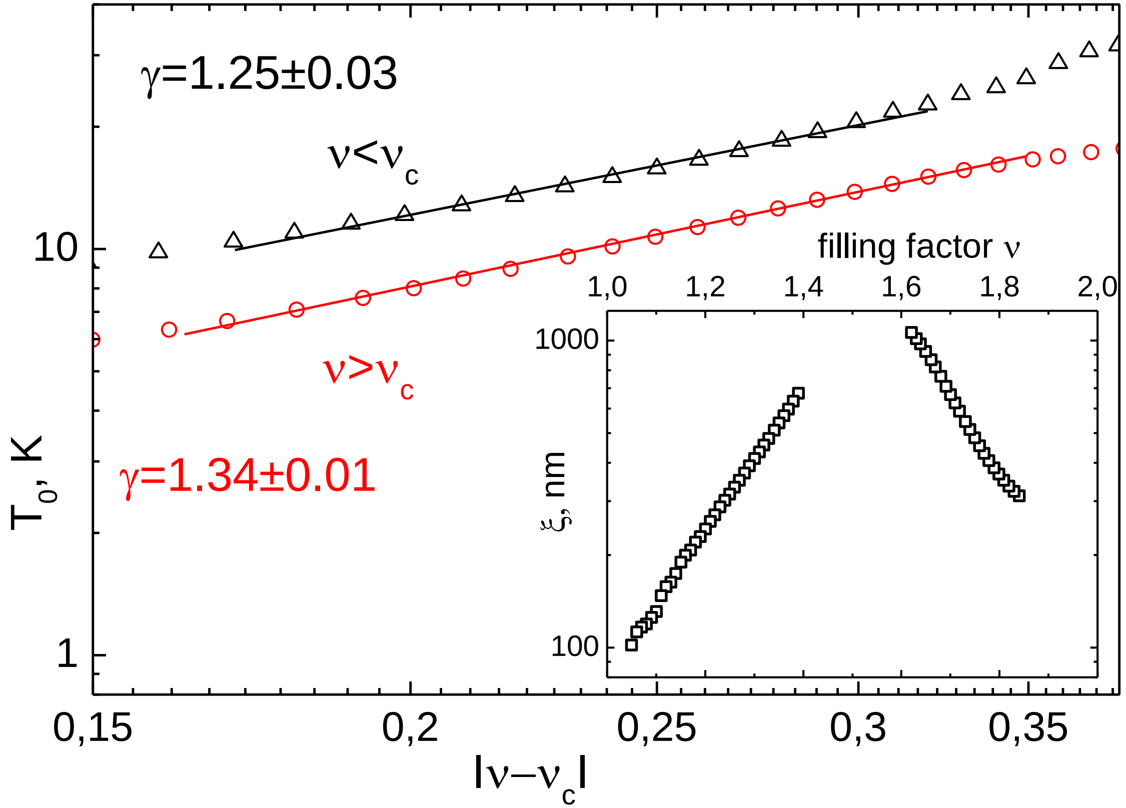


0,20
0,15
0,10
0,05
0,00
0,8
1,0
1,2
1,4
1,6
1,8
2,0
ρxx, h/e2
ν

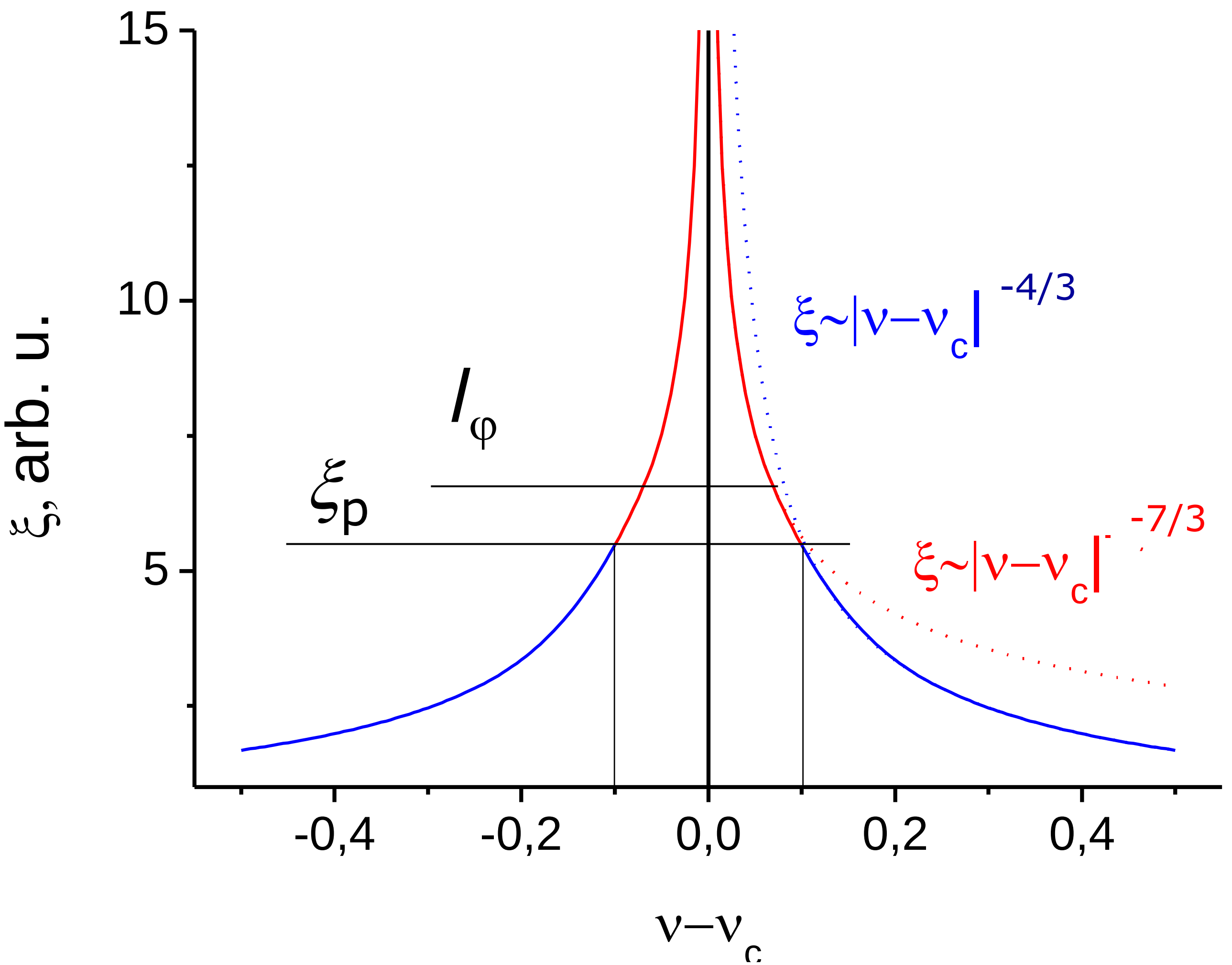
Plot of $\ln(\sigma_{xx}T)$ versus $1/T^{-1/2}$ at the low field side of $1\rightarrow 2$ transition. Various forms of *symbols* correspond to various values of ν (indicate near the *symbols*). *Solid lines* are a E-S's law fit of the data.



Characteristic temperature T_0 as a function of the distance to the critical point $|\nu - \nu_c|$ on both sides of the $1 \rightarrow 2$ transition (*open triangles* — $\nu < \nu_c$, open circles — $\nu > \nu_c$) on a double logarithmic scale. γ is determined as the gradient of the linear fit to $\ln(T_0) = \gamma \ln |\nu - \nu_c|$ (*solid lines*). *Insert* shows localization length ξ versus filling factor ν.



Schematic representation of the scaling behavior in the quantum Hall regime for the investigated sample.

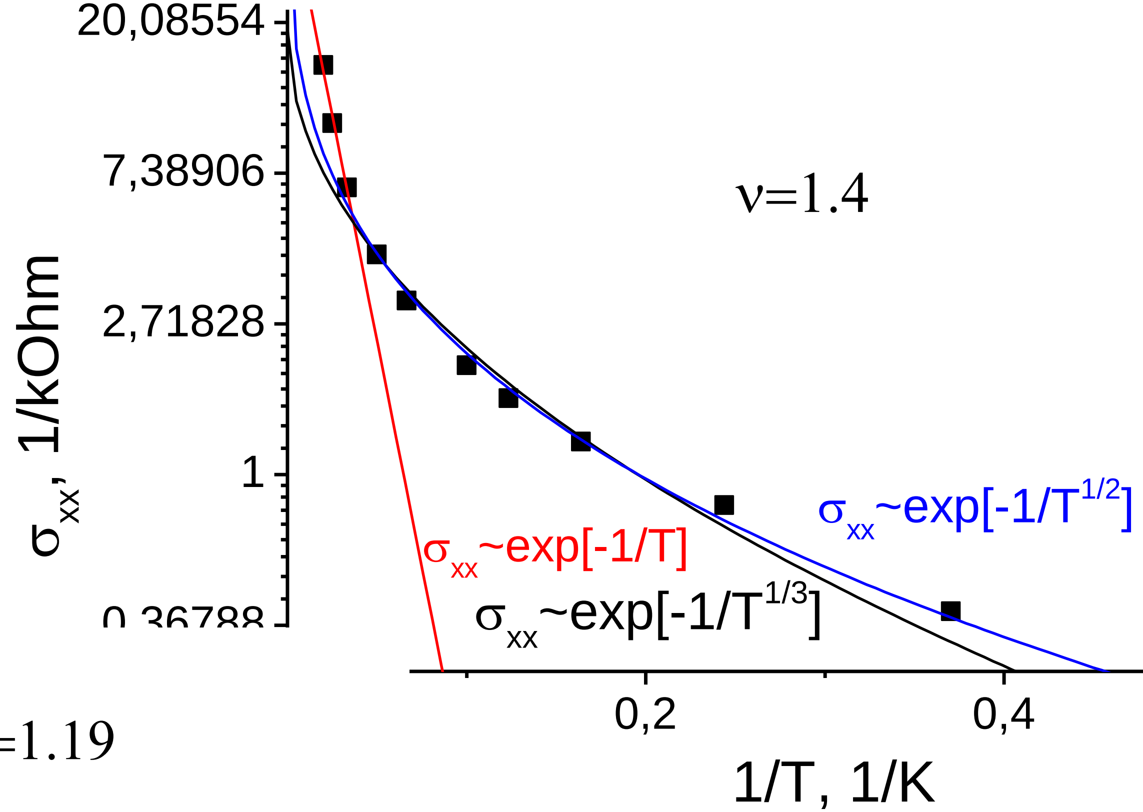


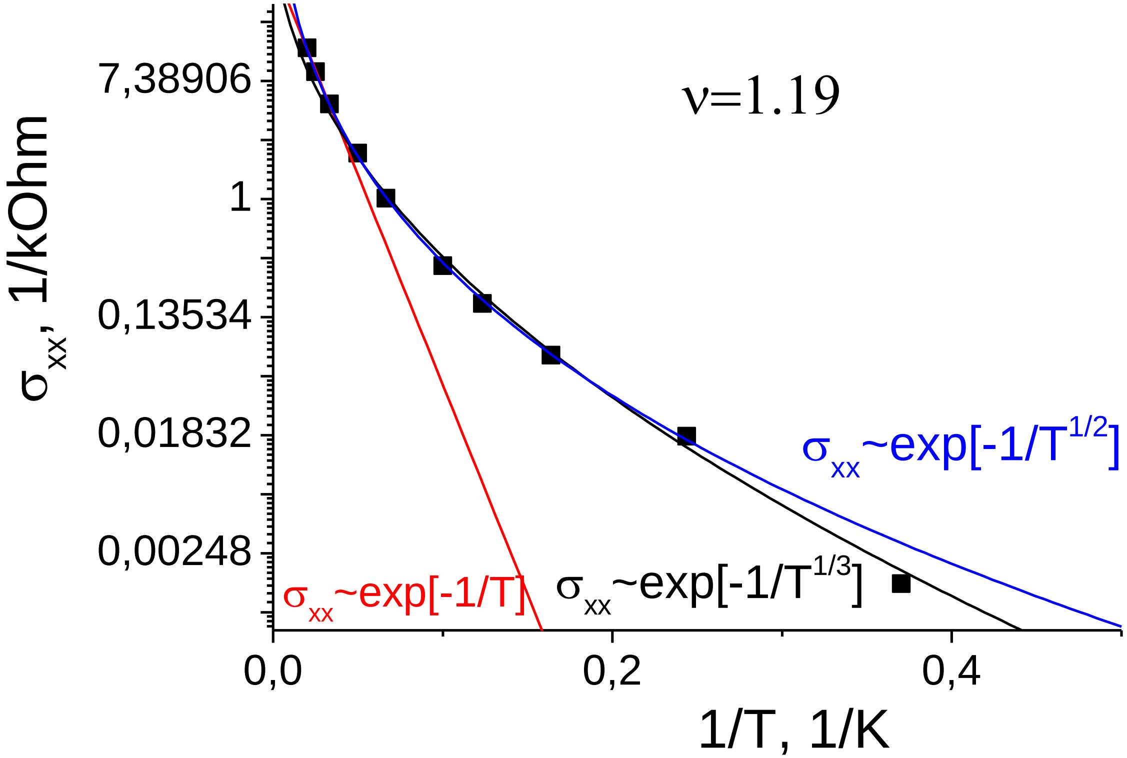
Conclusion

The feasibility of the temperature scaling regime for the plateau-plateau quantum phase transition is proved for the 2D HgTe-based heterostructures from the temperature dependences of conductivity in the transition region between the first and second quantum Hall plateaus. The scaling behavior $\nu_0(T) \sim T^{-\kappa}$ is observed for $1 \rightarrow 2$ plateau-plateau transition in T=(2-30) K with κ=0.54. This value is in rather good accordance with other experimental data for 2D system with large-scale impurity potential.

We have found that the hopping conductivity dominates in the regions of both first and second Hall plateaus and used the theory of hopping of interacting electrons to extract the magnetic-field dependence of the localization length, $\xi(B)$. An analysis of the ξ on B dependence revealed that for the HgTe quantum well in the investigated range of fields and temperatures, we deal with the process of classical percolation on localized states in the tails of the Landau levels.

Thank you for attention


20,08554
7,38906
2,71828
1
0,36788
σxx, 1/kOhm
ν=1.4
σxx~exp[-1/T1/2]
σxx~exp[-1/T]
σxx~exp[-1/T1/3]
0,2
0,4
1/T, 1/K


7,38906
1
0,13534
0,01832
0,00248
σxx, 1/kOhm
ν=1.19
σxx~exp[-1/T1/2]
σxx~exp[-1/T]
σxx~exp[-1/T1/3]
0,0
0,2
0,4
1/T, 1/K

Bennaceur 2012

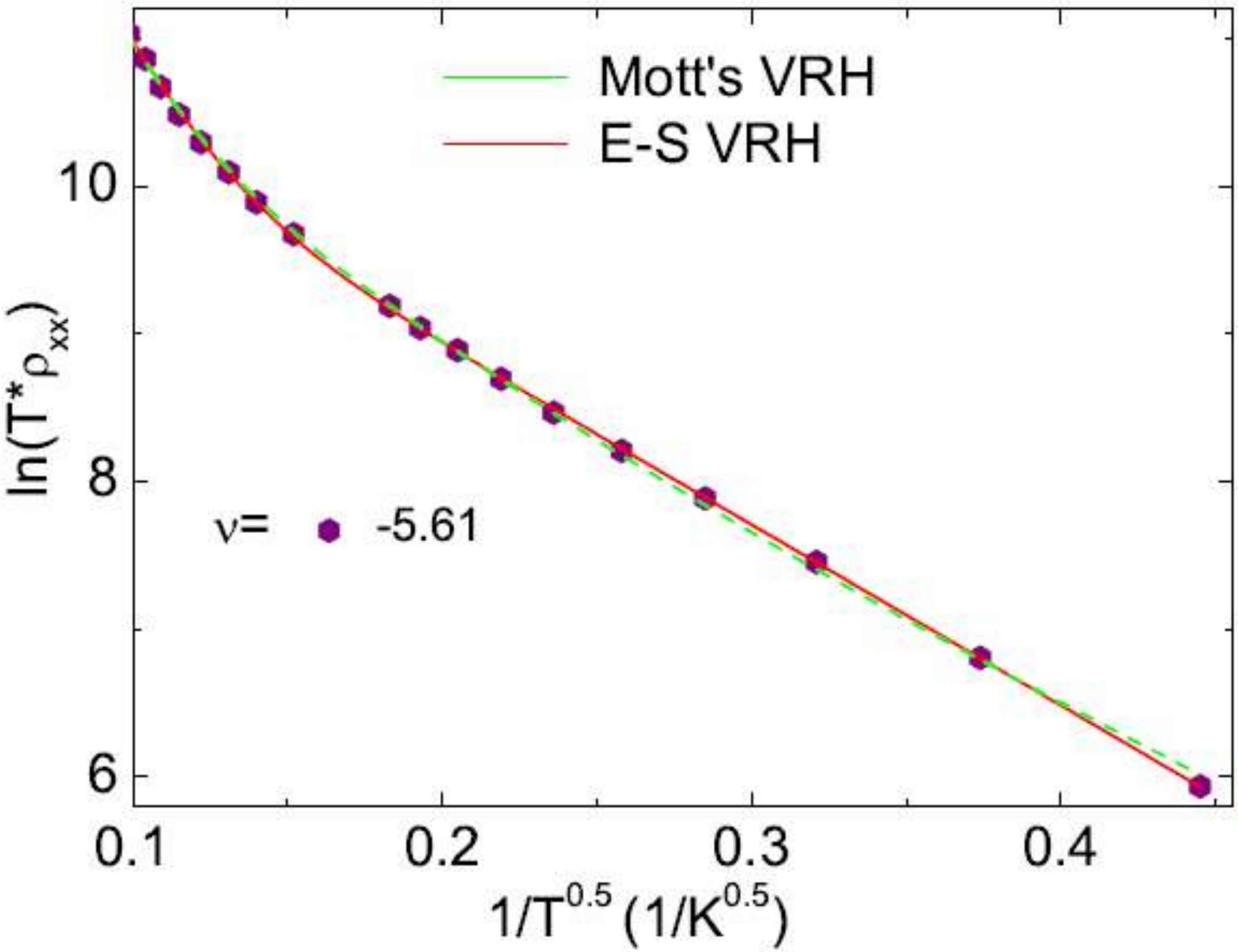


Figure 2: Plots of T_{xx} versus $1/T^{0.5}$ at 14.8T for $\nu = -5.61$ on sample S3. The red solid line are a E-S law's fit of the data while the green dashed line uses Mott's law