From the magnetic-field-driven transitions to the zero-field transition in two-dimensions

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For more than a decade it was widely accepted that two-dimensional electrons are insulating at zero temperature and at zero magnetic-field [1]. Experimentally it was demonstrated [2] that, when placed in a strong perpendicular magnetic field, the insulating phase turns into a quantum-Hall state at a carrier density towards the metal-insulator transition [3]. The density driven metal-insulator transition at zero magnetic-field, recently observed in high-quality two-dimensional systems [4], was unforeseen and, despite considerable amount of effort, its origins are still unknown [5-9]. In order to improve our understanding of the zero magnetic-field transition, we conducted a study of the insulator to quantum-Hall transition in low-density, two-dimensional, hole system in GaAs that exhibits the zero magnetic-field metal-insulator transition [10]. We found that, in the low field insulating phase, upon increasing the carrier density towards the metal-insulator transition, the critical magnetic-field of the insulator to quantum-Hall transition decreases and converges to the zero magnetic-field metal-insulator transition. This implies a common origin for both the finite magnetic-field and the zero magnetic-field transitions.

In Fig. 1a we plot the resistivity ($\rho$) of one of our samples as a function of magnetic-field ($B$) at several temperatures, with the hole-density ($p$) held fixed. At $B = 0$ the system is insulating as indicated by a rapidly increasing $\rho$ as the temperature ($T$) approaches zero. The insulating behavior is maintained for $B < B^l_c$. For $B > B^l_c$, a quantum-Hall (QH) state ($\nu = 1$, where $\nu$ is the Landau-level filling factor) is observed with $\rho$ tending to zero upon lowering of $T$. We identify $B^l_c$ as the point where the temperature coefficient of resistivity (TCR) changes its sign, with the critical point of the insulator-to-QH transition [3]. At still higher $B$, beyond the $\nu = 1$ QH state, the system turns insulating and a second T-independent transition point is seen at $B^H_c$. $B^H_c$ therefore marks the critical $B$ of the QH-to-insulator transition [11]. Following the path set by earlier studies [2-3] we focus, for now, on the low-$B$ transition and follow, in Figs. 1b-1e, the evolution of the critical point $B^l_c$ as we increase $p$.

Data obtained from the same sample at successive increases of the density are shown in Figs. 1b-1e. As in Fig. 1a, the insulator-to-QH transition point is evident in Fig 1b, but the transition point “moves” to a lower $B$. This trend continues in Fig. 1c until finally, in Fig. 1d, the crossing point disappears. Along with this shift in $B^l_c$, we notice in Figs. 1a-1c, that the insulating behavior at $B = 0$ becomes weaker until, in Fig. 1d, $\rho$ at $B = 0$ is $T$-independent. In the next graph, Fig. 1e, the system has crossed over into its metallic phase and no transition, or $T$-independent point, is seen implying that the density of Fig. 1d ($p = 1.34 \times 10^{10}$ cm$^{-2}$) is the critical density of the metal-insulator transition (MIT) at $B = 0$. This $B = 0$ transition is the MIT in two dimensions (2D) first reported by Kravchenko et al. for Si samples [1]. Our main result can now be stated: Upon increasing $p$, $B^l_c$ gradually tends to lower $B$’s, eventually converging to the $B=0$ MIT which, for this sample, takes place at $p = 1.34 \times 10^{10}$ cm$^{-2}$.

To complement our $p$-dependence study of the $B$-driven transitions we will next focus on the effect of a perpendicular $B$ on the $p$-driven transition. Our new starting point is the more conventional experimental demonstration of the $B = 0$ MIT in 2D. In Fig. 2a we plot $\rho$ as a function of $p$ at several $T$’s and at $B=0$. A $T$-independent crossing point is seen here as well (at $p_c = 1.34 \times 10^{10}$ cm$^{-2}$), marking the transition from insulating behavior for $p < p_c$ to metallic behavior for $p > p_c$. We then repeat, in Figs. 2b-2e, the measurement of Fig. 2a at different values of $B$. In Figs. 2b and 2c, $p_c$ shifts to a lower value, a trend which reverses for $B \geq 0.35T$ (Figs. 2d-2e). This trend reversal of $p_c(B)$ is accompanied by the development of non-monotonic dependence of $\rho$ on $p$, which is a precursor to the quantum Hall effect (QHE). We now combine these $p_c(B)$ results with the $B_c(p)$ of Fig. 1, to plot a comprehensive phase diagram of our system in the $B - p$ plane.

The phase diagram obtained from our data is shown in Fig. 3, where we plot the $B$ and $p$ coordinates of each one of the transitions. Separate symbols are given to $B^l_c$ and $B^H_c$, defined in Fig. 1, and to $p_c$ from Fig. 2. Several points emerge from inspecting the resulting phase diagram. First, we note that the results obtained from
the two data sets (fixed \(p\) and fixed \(B\) measurements) are mutually consistent. Second, for fixed \(p\)'s between 0.88 and \(1.33 \times 10^{10}\) cm\(^{-2}\) the low-\(B\) insulating phase first turns metallic and then reappears at high \(B\). This reentrant nature of the insulating phase is clearly reflected in the \(B\) traces of Figs. 1a-1c. And third, the low \(B\) region of the phase boundary reiterates the main result of our work and clearly depicts the continuous evolution of the transition from high-\(B\) to the \(B=0\) MIT. The relation between the transition at finite \(B\) and the MIT transition at \(B=0\), suggests that similar processes govern the transport for both transitions [14].

Fig. 3 also includes the high-\(B\) side of the phase diagram \((B_c^H)\). In fact, the low and high \(B\) regimes are smoothly connected to form a single phase-boundary line. It is common practice to describe the finite-\(B\) transitions in the language of quantum phase transitions [13]. If we assume that the phase-boundary line of Fig. 3 comprises a set of quantum critical points, it is possible that universal features should be observed in its vicinity. To test this proposition we examine the value of \(\rho\) at the transition points, \(\rho_c\). In Fig. 4a we plot \(\rho_c\) of our transitions as a function of \(B\). Overall, \(\rho_c\) is not constant, its value changing by almost a factor of 4 over our \(B\) range. However, at very low as well as very high \(B\), \(\rho_c\) approaches a value close to \(h/e^2\), the quantum unit of resistance. Although for our sample, at \(B=0\), \(\rho_c\) is close to \(h/e^2\) we wish to point out that the value of \(\rho_c\) at \(B=0\) obtained from other samples varies by an order of magnitude, between 0.4 and \(4h/e^2\) [10].

So far we have shown that \(B_c^L\), \(B_c^H\) and \(\rho_c\) define a common phase boundary line in the \(B-p\) plane, and that at the intermediate \(B\) range along this phase boundary \(\rho_c\) significantly deviates from \(h/e^2\), its value near \(B=0\) and at high-\(B\). It is instructive to consider the dependence of \(\rho_c\) on \(p\), rather than on \(B\). In Figs. 1a-1c we can readily see the general trend: \(\rho_c\) of the low and high-\(B\) transitions at fixed \(p\) are very close to each other. To test this result for our entire range of \(p\) we plot, in Fig. 4b, \(\rho_c\) versus \(p\) obtained from our data. We see that the two transitions have collapsed onto a single curve for our entire range of \(p\). This result demonstrates that for a given carrier-density \(\rho_c\) of the low and high-\(B\) transitions is the same. This supports the notion of symmetry between these transitions [17].

A possible relation between different transitions in 2D systems was noted by Jiang et al. [2] who pointed out the similarities between the insulator-to-QH and the insulator-to-superconductor transitions. Theoretical basis for such similarity was introduced in ref. [14]. In our work we found a relation between the finite \(B\) insulator-to-QH transition and the metal-insulator transition at \(B=0\). Since both transitions are measured in the same 2D system, we were able to continuously transform one to the other. This raises the possibility that both transitions share a common physical origin.

**Methods**

The sample used in this study is a \(p\)-type, inverted semiconductor insulator semiconductor (ISIS) sample grown on (311)A GaAs substrate with Si as a \(p\)-type dopant. In an ISIS device the carriers are accumulated in an undoped GaAs layer lying on top of an undoped AlAs barrier, grown over a \(p^+\) conducting layer. This \(p^+\) conducting layer is separately contacted and serves as a back-gate. The hole carrier-density \((p)\) is varied by applying voltage \((V_g)\) to the back-gate. The sample was wet-etched to the shape of a standard Hall-bar and the measurements were done in a dilution refrigerator with a base \(T\) of 57 mK, using AC lock-in technique with an excitation current of 1 nA flowing in the [01\(\bar{1}\)] direction.

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Acknowledgments.

The authors wish to thank Efrat Shinshoni, M. Hilke and Amir Yacoby for very interesting discussions. This work was supported by the NSF, the BSF and by a grant from the Israeli Ministry of Science and The Arts.

FIG. 1. Isotherms of the magnetor-resistance data of sample H324Bc at various densities. The traces are color coded with blue being low and red being high T. T=63, 122, 177, and 217 mK (a) p = 1.09 · 10^{10} \text{ cm}^{-2}. (b) p = 1.21 · 10^{10} \text{ cm}^{-2}. (c) p = 1.26 · 10^{10} \text{ cm}^{-2}. (d) p = 1.34 · 10^{10} \text{ cm}^{-2}. (e) p = 1.42 · 10^{10} \text{ cm}^{-2}.

FIG. 2. Isotherms of the resistance versus p of sample H324Bc at various B’s. The traces are color coded with blue being low and red being high B. (a) B=0 T at T=57, 120, 160, and 214 mK. (b) B=0.2 T at T=58, 121, 160, and 217 mK. (c) B=0.4 T at T=60, 98, 148, and 212 mK. (d) B=0.6 T at T=59, 122, 161, and 217 mK. (e) B=0.9 T at T=59, 122, 161, and 217 mK.

FIG. 3. B and p coordinates of the crossing points derived from data similar to those of Figs. 1a-1e and Figs. 2a-2e. Open diamonds denote p_c, solid diamonds denote B_L^c and solid triangles denote B_H^c. The arrow points to the B=0 MIT.

FIG. 4. (a) p_c plotted as a function of B. Open diamonds denote p_c from p_c data, solid diamonds denote B_L^c data and solid triangles denote B_H^c data. (b) p_c plotted as a function of p.
Hanein et al. Fig. 1
Hanein et al. Fig. 2
$p \times 10^{10} \text{ cm}^{-2}$

$B=0$ MIT

TCR>0 (Metallic)

TCR<0 (Insulating)

$B_c$

$B_c^L$

$B_c^H$

$p_c$

Hanein et al. Fig. 3
Hanein et al. Fig. 4