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LETTER TO THE EDITOR

Excitation gaps in the fractional quantum Hall effect in tetracene

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Abstract

We have measured the temperature dependence of the fractional quantum Hall effect at filling factors $\nu = 1/3$, $2/3$, and $2/5$ in tetracene in order to determine the associated excitation gaps. The stronger two-dimensional confinement of the hole gas compared to conventional inorganic semiconductors as well as the strong electron–electron interactions result in larger excitation gaps. As a result, the fractional quantum Hall effect is observable at moderately high temperatures. An excitation gap of 24 K at 9 T is estimated for $\nu = 1/3$.

The fractional quantum Hall effect (FQHE) [1–3], which occurs in high-mobility two-dimensional electron or hole systems subject to a strong perpendicular magnetic field, is ascribed to the existence of an incompressible quantum liquid at certain rational filling factors. In this regime, electron–electron interactions dominate over disorder effects compared to the integral quantum Hall effect (IQHE) case. As a result, the motion of electrons in the FQHE regime is no longer driven by the Pauli exclusion principle as in the case of the IQHE but by reduction in Coulomb energy. Recently, we have demonstrated that the FQHE is also observable in high-quality organic metal–insulator–semiconductor (MIS) structures [4]. In comparison to the case for conventional inorganic semiconductors, such as Si or GaAs, the effects of electron–electron interaction are expected to be enhanced in such organic materials due to the high effective mass m^* of the charge carriers and the low dielectric constants ε (in the range of 3 to 4). Due to deviations from a strictly two-dimensional system, mixing of Landau levels, and disorder, the excitation energies in the FQHE regime in GaAs have been found to be significantly smaller than the theoretical value [5–7]. Since the excitation energy spectrum can give significant insight into the underlying physical processes, we investigated the temperature dependence of the magnetotransport in the FQHE regime of tetracene MIS structures in order to analyse the influence of strong Coulomb interaction in this system.

High-quality tetracene single crystals have been grown from the vapour phase in a stream of hydrogen [8] using pre-purified starting material. MIS structures have been prepared using sputtered Al_2O_3 as the gate dielectric layer and gold as the gate electrode [4, 9]. Ohmic contacts to the two-dimensional hole gas at the Al_2O_3/tetracene interface were achieved by using thermally evaporated gold. The hole density in this system can be adjusted by means of the applied gate bias of the field-effect structure. We have studied high-mobility samples of

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tetracene MIS structures with hole densities ranging from 4×10^{10} to approximately 10^{11} cm^{-2}. Peak mobilities between 10^5 and 2.5×10^5 cm^2 V^{-1} s^{-1} have been achieved in such structures [4]. Taking into account the high effective hole mass of $1.3\,m_e$, a relaxation time τ_0 in the range of 10^{-10} s can be estimated. This corresponds to a disorder energy ($\approx\hbar/\tau_0$) in the range of 5–10 μeV reflecting the high quality of the samples investigated. Magnetotransport measurements were carried out in the range from 10 to 1.7 K with magnetic fields up to 9 T.

Figure 1 shows the diagonal resistance R_{xx} of a tetracene MIS sample with a hole density of 6.12×10^{10} cm^{-2} as a function of magnetic field. Similar R_{xx}-traces have been obtained for different carrier concentrations and high-quality samples. Distinct minima at filling factors $\nu = p/(2p+1)$ of 2/3, 3/5, 3/7, 2/5, and 1/3 are observable. Moreover, quantized Hall plateaus can be identified at these rational filling factors in such tetracene MIS structures [4]. In the temperature range from 1.7 to 10 K the magnetoresistance R_{xx} is thermally activated ($R_{xx} = R_{xx,0}\exp(-\Delta/2k_BT)$; see figure 2), which allows the determination of the excitation gap Δ. The composite-fermion theory result for the excitation gaps of the FQHE states at filling factor ν is approximately summarized by [10, 11]

$$\Delta^{(\nu)} \approx \frac{C}{|2p+1|}\frac{e^2}{4\pi\varepsilon_0\varepsilon l} \tag{1}$$

where $C \approx 0.32$ and $l = (\hbar/(eB))^{1/2}$ is the magnetic length. This behaviour was conjectured in the context of the Chern–Simons approach [11], and then confirmed by an explicit evaluation of $\Delta^{(\nu)}$ from the composite-fermion wave functions [10, 12]. However, the effect of the finite thickness of the two-dimensional hole gas will lead to a reduction of the gap [10, 13] due to the deviation from the strictly two-dimensional character. The effect of the finite layer thickness can be estimated using the dimensionless parameter bl, where b is the Fang–Howard parameter [14]. In the case of the tetracene MIS structures investigated, b is of the order of (20 Å)$^{-1}$ resulting in values of bl of approximately 4 or higher, showing the strong confinement of the hole gas. With reasonable accuracy the gap dependence on bl can be approximated using the

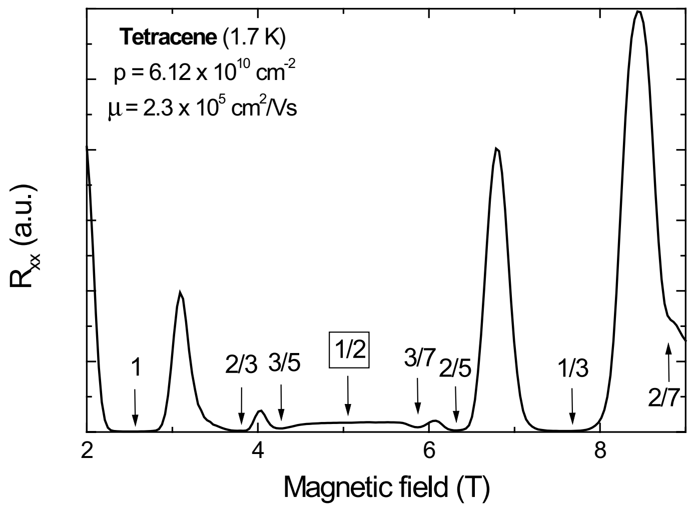

Figure 1. The magnetoresistance R_{xx} of a tetracene MIS (peak mobility 2.3×10^5 cm^2 V^{-1} s^{-1}) structure at 1.7 K for fields up to 9 T. The hole density is 6.12×10^{10} cm^{-2}. The magnetoresistance minima at the fractions 1/3, 2/5, 3/7, 3/5, and 2/3 are clearly observable.

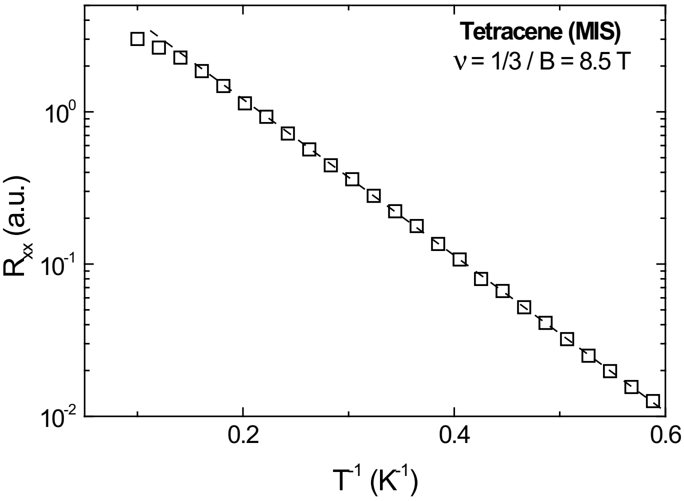

Figure 2. The magnetoresistance R_{xx} of a tetracene MIS (peak mobility 2.3×10^5 cm^2 V^{-1} s^{-1}) at filling factor $\nu = 1/3$ and for magnetic field $B = 8.5$ T as a function of inverse temperature revealing a thermally activated behaviour. The excitation gap $\Delta^{1/3}$ can be determined from this temperature dependence.

following expression [13, 15]:

$$\frac{\Delta^{(\nu)}}{\Delta^{(\nu)}_{b^{-1}=0}} \approx 0.9966 - 0.6170(bl)^{-1} + 0.1407(bl)^{-2}. \qquad (2)$$

Hence, the effect of the nonzero thickness leads to a more or less ν-independent reduction of C and, therefore, $\Delta^{(\nu)}$. Disorder-induced broadening is generally treated by reducing the gap $\Delta^{(\nu)}$ by a constant value Γ, which is related to the quantum lifetime τ^* of the composite fermions ($\Gamma \approx \hbar/\tau^*$) [16]. In figure 3 the excitation gap is shown as a function of magnetic field B for filling factors 1/3 and 2/3. A good agreement between the experimental data for the filling factors 1/3 and the reduced gap according to equations (1) and (2) is observed ($\Gamma \approx 0$). This is quite surprising, since the effect of Landau level mixing has been neglected, which should lead to an additional correction [17]. This correction should be quite large due to the large effective mass of the holes in tetracene. Due to the low dielectric constant ε and the almost strictly two-dimensional behaviour, excitation gaps as high as 25 K have been observed in tetracene MIS structures at moderate fields of 9 T. This leads to the observation of the FQHE at moderately high temperatures in these organic semiconductors.

In the case of $\nu = 2/3$ the experimental data at low magnetic fields are significantly below the gap values calculated using equations (1) and (2). Since the effect of disorder should result in a ν-independent reduction of $\Delta^{(\nu)}$, this can be excluded. Moreover, since the effect of Landau level mixing should be more pronounced for $\nu = 1/3$ than for $\nu = 2/3$ [17], a different mechanism must be responsible for the reduced excitation gap. A possible explanation might be the effect of the spin polarization of the FQHE state on the gap energy. It has been shown for GaAs that the 2/3 state is unpolarized at low magnetic fields [18], which leads to a reduction of the excitation gap [19, 20]. This might explain the deviation of the experimental data for $\nu = 2/3$ in tetracene MIS structures.

In figure 4 the excitation gap for 2/5 ($p = 2$) is shown as a function of magnetic field B. Compared to that for the 1/3 state, the gap is reduced in accordance with equation (1). Like for the experimental results for 1/3 ($p = 1$), we observe a good agreement of the

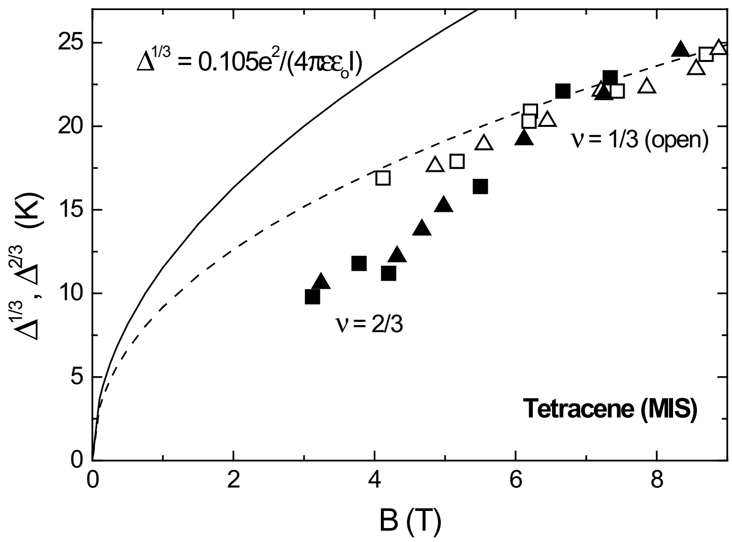

Figure 3. The magnetic field dependence of the excitation gaps $\Delta^{1/3}$ and $\Delta^{2/3}$ at filling factors 1/3 (open symbols) and 2/3 (closed symbols) for two different samples (squares, triangles). A good agreement with the theoretical value of $\Delta^{1/3}$ is observed taking into account the finite thickness of the two-dimensional hole gas. The deviations for $\nu = 2/3$ at low magnetic fields might be related to a transition from an unpolarized to a completely polarized state.

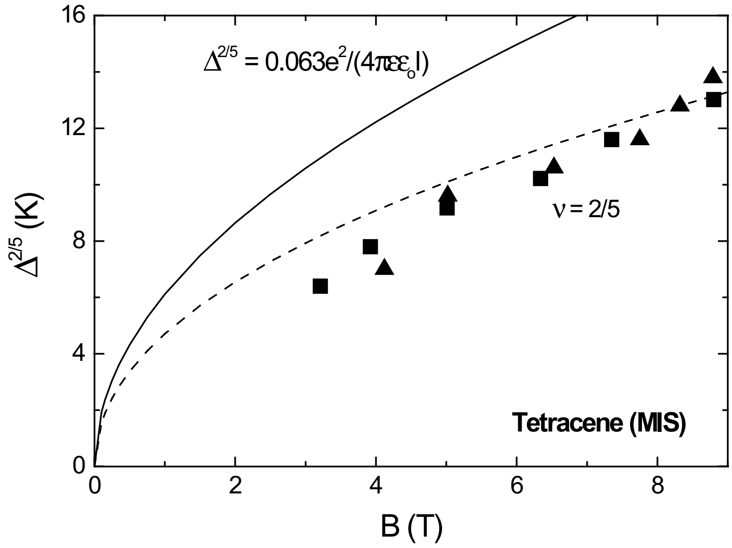

Figure 4. The magnetic field dependence of the excitation gap $\Delta^{2/5}$ at filling factor 2/5 for two different samples (squares, triangles). A good agreement with the theoretical value of $\Delta^{2/5}$ is observed taking into account the finite thickness of the two-dimensional hole gas.

experimental data for 2/5 and the theoretical estimation taking into account just the finite-thickness corrections (equation (2)). The slight deviations at low magnetic fields might also be related to spin-polarization effects. Nevertheless, it is puzzling that Landau level mixing seems not to significantly affect the excitation gap $\Delta^{(\nu)}$ in this system.

In a simple interpretation of the composite-fermion theory, the excitation gaps $\Delta^{(\nu)}$ are associated with an effective mass m^*_{CF} of the composite fermion [6, 11, 16]:

$$\Delta^{(\nu)} = \hbar \frac{eB^*}{m^*_{CF}} \tag{3}$$

where B^* is the effective field experienced by the composite fermion, $B^* = B - B_{1/2}$. Using the experimental data for 1/3 and 2/5 we obtain a value of $(0.15 \pm 0.05)\, m_e$ for the composite fermions in the tetracene MIS structures. Since m^*_{CF} is a result of the strong electron–electron interaction, this value is significantly smaller as in conventional GaAs samples [6, 16]. This manifests the strong electron–electron interactions in these organic semiconductors.

In conclusion, the excitation gaps in the FQHE regime in tetracene MIS structures were obtained from temperature-dependent magnetotransport measurements. Due to the strong confinement of the two-dimensional hole gas as well as due to the strong electron–electron interactions, the excitation gaps are significantly larger than in conventional inorganic semiconductors. As a result of this, the FQHE becomes observable at higher temperatures.

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