Gap opening in the zeroth Landau level of graphene

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We have measured a strong increase of the low-temperature resistivity $\rho_{xy}$ and a zero-value plateau in the Hall conductivity $\sigma_{xy}$ at the charge neutrality point in graphene subjected to high magnetic fields up to 30 T.

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Graphene

"Graphene is a single planar sheet of sp²-bonded carbon atoms that are densely packed in a honeycomb crystal lattice. From a physicist point of view, graphene is the basic structural element for all other graphitic materials including graphite, carbon nanotubes and fullerenes." (Wikipedia)

"Electrons in graphene, obeying a linear dispersion relation, behave like massless relativistic particles. This results in the observation of a number of very peculiar electronic properties - from an anomalous quantum Hall effect to the absence of localization. It also provides a bridge between condensed matter physics and quantum electrodynamics, and opens new perspectives for carbon-based electronics." (M.I. Katsnelson)
Charge Neutrality point
Monolayer graphene on Si/SiO$_2$
Doped Si
Annealed at 390K
$\mu$ = 0.47 m$^2$/Vs to 1 m$^2$/Vs
= 1 nA at 400 mk
Gap opening in 0\textsuperscript{th} LL-T and B-field dependence

At $B=0$, $E=\pm\hbar|k|$.

$B \neq 0 \quad E_N=\pm c(2e\hbar N)^{1/2}$, $N \geq 1$, four fold degenerate.

0th LL @ $N=0$ half filled with electrons and half filled with holes.

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Arrhenius plot $\sigma_{xx} = \exp(-\Delta_a/k\Gamma)$
$\Gamma_0 = 30K$
Gap opening in 0\textsuperscript{th} LL-Model

DOS
N=0, 2eB/h
N\neq 0, 4eB/h

Kubo Greenwood formalism for disorder

\[ \rho_{xx} = \frac{\sigma_{xx}}{\left(\sigma_{xx}^2 + \sigma_{xy}^2\right)} \rightarrow 0 \]
Gap opening in 0th LL-Model- Symmetry breaking and interaction induced gap

Symmetry Breaking at CNP:-
ν=−2 plateau with $\rho_{xy}=−h/2e^2=12.9$ kΩ
to the ν=+2 plateau at $\rho_{xy}= h/2e^2$
electrons and holes coexist below and above the CNP
graphene behaves as a compensated semimetal

Interaction induced gap:-
$I=e^2/4\pi\varepsilon_0\varepsilon_rB =1400$ K at 30 T
exceeds width of the 0 energy LL $\Gamma_0$ by two orders
of magnitude.

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Gap opening in 0\textsuperscript{th} LL- Conclusions

- Observed transport properties of 0\textsuperscript{th} LL at low T, high B
- Strong increase in longitudinal resistance with a zero crossing in the Hall resistivity at the CNP
- A flat plateau in the Hall conductivity with a thermally activated minimum in the longitudinal conductivity.
- Opening of a gap in the density of states of the 0th LL,
- Field dependent splitting of the lowest LL
- Co-existance of electrons and holes in split zero energy LL