High-Field Study of Yb-Doped AlGaAs/GaAs Two-Dimensional Electron Systems

Basic Research for a Quantum Hall State-Mediated Quantum Computing Device

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Two-dimensional electron systems (2DES) in high magnetic fields are known to exhibit exact resistance quantization, as described by the quantum Hall effect (QHE). The electronic state of the QHE is characterized by its long mean free path or semi-long-range coherence. Combination of the semi-coherent states and semi-localized states of certain impurities (e.g., rare earth ions, quantum dots) may open up possibilities for new devices, such as quantum coherent devices and quantum computers. To investigate this possibility, we have grown 2DES samples with Yb-doping and performed basic measurements in multiple-extreme conditions to clarify the interaction between these rare-earth impurities and the 2DES. Under examination in this study are typical AlGaAs/GaAs heterostructures with and without Yb-ion doping near the 2DES. They have been grown with molecular beam epitaxy and fabricated into standard Hall bar geometries by means of photolithography. Transport and optical measurements under various illumination conditions were performed in magnetic fields up to 25 T at ~1.5 K. In the case of the non-doped samples, clear QHE properties were found in both transport and photoluminescence signals. On the other hand, quantum oscillations were not observed in the Yb-doped sample, and measurements were largely affected by weak illumination around the 1-μm wavelength. Additionally, this sample's contacts exhibited non-ohmic properties even with different conditions of contact fabrication. We will discuss these results in terms of Yb-ion-related states and their interaction with the 2DES.

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Motivation for Yb-Doping

- Optical Devices: Wavelengths of ~1 μm arises from 4f intra-level transitions in Yb^{3+} ions. These wavelength can be used in optical communications devices.
- Quantum Computing: Yb spin states manipulated by local sensing equipment are a possible candidate for quantum bits (qubits). Interaction between multiple qubits could be mediated by the macroscopic coherence of quantum Hall states.

Our Experiment

We fabricated both undoped and Yb-doped AlGaAs/GaAs heterostructures with standard Hall bar geometries. To investigate the properties of each sample's 2DEG, we made transport and magneto-photoluminescence measurements. Data were taken at low temperatures and high magnetic fields under a variety of sample illumination conditions.

Sample Preparation

Molecular Beam Epitaxy

T228 Sample

GaAs	20 nm
AlGaAs:Si	40 nm
AlGaAs	40 nm
←Si δ-dope	
AlGaAs	40 nm
2DEG	
GaAs	30 nm
AlGaAs	10 nm
GaAs	

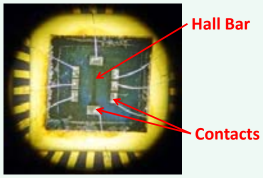
Yb116 Sample

GaAs	20 nm
AlGaAs:Si	40 nm
AlGaAs	100 nm
Si δ-dope→	
AlGaAs	20 nm
AlAs:**Yb**	10 nm
AlGaAs	10 nm
2DEG	
GaAs	

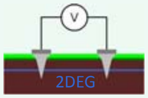
Substrate temperature: 630° C, $Al_{0.3}Ga_{0.7}As$

Molecular Beam Epitaxy Machine

Hall Bar Fabrication



Appearance of Sample



Side view: After annealing, the contacts are in contact with the 2DEG.

×2 [
- Resist-coating
- Pre-bake
- Photolithography
- Post-bake
]
- Wet chemical etching
- Metal evaporation
- Annealing
- Wiring

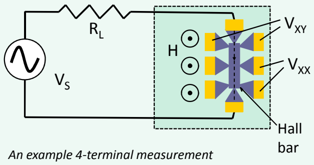
Experimental Setup

High magnetic field

We used both a superconducting magnet (up to 15 T) and a specially-designed water-cooled magnet (25 T). Each magnet has a cryostat and pump system, which was used to achieve experimental temperatures of ~1.5 K. Samples were inserted into the magnets using a probe with optical fiber and copper wiring.


The 25-T water-cooled magnet at NIMS

Transport Measurements



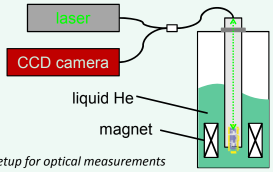
An example 4-terminal measurement
Magnetic field H is perpendicular to the sample surface.
V_{xx} – measured parallel to current direction
V_{xy} – measured perpendicular to current direction

An AC excitation signal wired in series with a large load resistance and the contacts on opposite ends of the Hall bar. *XX* and *XY* (Hall) voltage were measured simultaneously using lock-in amplifiers.

Illumination conditions tested:
- dark
- strong 532-nm, solid-state laser
- monochromatic infrared (900-1000 nm) from a bulb

Optical Measurements

We shone a green, solid-state laser (532 nm) into the optical fiber of the probe. The photoluminescence (PL) signal returned via optical fiber to a spectrometer, which monitored light intensity over a range of wavelengths simultaneously.



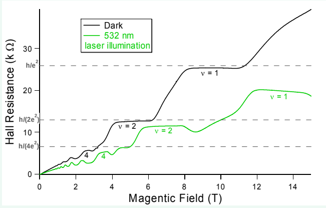
Setup for optical measurements

Optical and Transport Data

T228: Typical Quantum Hall System

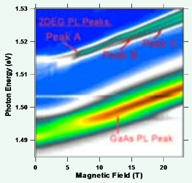
Transport

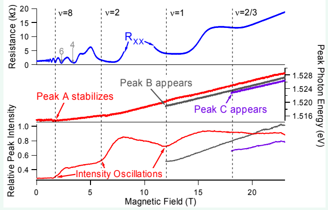
- Under dark conditions, we observe nearly ideal QHE. Plateaux become clearer with higher electron mobility.
- Under strong illumination of the 532 nm laser, carrier concentration increases from $2.6\times10^{11}cm^{-2}$ to $3.4\times10^{11}cm^{-2}$. R_{XY} plateaux decrease from their QHE values, while R_{XX} increases from zero in these regions.



Optical

- Oscillations in the intensity of Peak A are correlated with some integer filling factors.
- New PL peaks appear at higher magnetic fields (ν = 1: 12 T, ν = ⅔: 18 T). This is likely due to the energy gain from the typical spin configuration at 1 and ⅔.

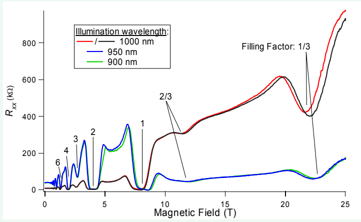


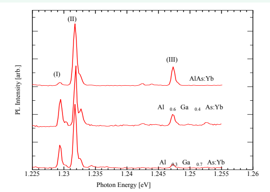


Yb116: Effects of Yb-Doping

Transport

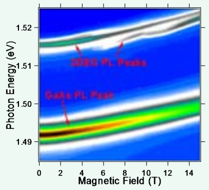
- Clear Shubnikov-de Haas oscillations are observed in R_{XX} data **only** when the sample is illuminated (900-1000 nm light).
  - This illumination effect shows the controllability of the metal-insulator transition in Yb-doped quantum structures.
- *XX* resistance data differs greatly between 1000 and 950 nm illumination wavelengths.





Optical

- PL intensity oscillations are **not** observed in the Yb-doped sample. This is liked due to localization in the sample caused by the Yb atoms.
- Photoluminescence from a bulk GaAs:Yb sample is observed to be ~1.23 eV (λ ≈ 1 μm).

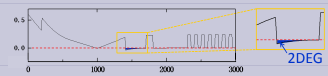


Conclusions

In the undoped T228 heterostructure sample, we can observe oscillations in both transport and optical data. The QHE manifests itself clearly, and appearance of new photoluminescence peaks corresponds to the filling factors 1 and ⅔. Remote Yb-doping appears to cause localization in the 2DEG, but the metal-insulator transition can easily be controlled using light in the 1 μm wavelength range. With the Yb116 sample illuminated oscillations in R_{XX} are very distinct, but no oscillations were detected in the optical data.

What is the QHE?

Quantum Hall effect (QHE) is the name given to the exact resistance quantization exhibited by a 2-dimensional electron gas (2DEG) at low temperatures and high magnetic fields. At integer "filling factors" ν, R_{XY} plateaus at value $h/(\nu * e^2)$ while R_{XX} becomes exactly zero. This result is independent of sample size and material. At higher magnetic fields, additional R_{XY} plateaux can be observed as per the fractional QHE (fractional values of ν).



Conduction band and Fermi level of T228 sample.
The 2DEG forms in a quasi-triangular potential well just below the Fermi level.

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