Ultra-low Electron Temperatures in 2D Electron Gases

Master Thesis Presentation
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Outline

Thermal smearing
Cold electrons
  Kapitza resistance
Mixing chamber design
Hall Bar sample
Hall effect
Electron temperature measurement
Outlook
  Adiabatic demagnetization
Thermal activation

Example: **Keto-enol tautomerism**

$C_6H_{10}O_3$: Which structure is the true one?

$$k_\rightarrow = Ae^{-E_a/RT}$$ Arrhenius equation

http://de.wikipedia.org/wiki/Acetessigester
http://www.hutters-online.de/publikationen/dipl_a.html
Thermal activation

Example: Singlet-Triplet transition in a $\text{C}_{60}$ Molecule


$T_b = 35\text{mK} \quad T_e = 50\text{mK}$
How to get electrons cold

Electrons are usually warmer than $^3\text{He}/^4\text{He}$ mixture

Heat input:
- Joule heating $dQ = I^2 R$
- Thermal conduction along leads $\rightarrow$ thermal anchoring
- RF noise $\rightarrow$ Filters

Cooling power often limited by Kapitza resistance $R_K$

$$dQ = I^2 R$$

$R = R_{\text{Th}} + R_K$
Kapitza resistance

Phonons crossing the boundary mediate the exchange

**Acoustic mismatch theory** accounts for

- Boundary scattering of phonons
  \[ \alpha_c = \arcsin \left( \frac{v_{He}}{v_{solid}} \right) \approx 3^\circ \]
- Difference in acoustic impedance
  About 1:10^5 phonons can cross the boundary

\[ R_K = \frac{\Delta T}{\dot{Q}} = \frac{c}{AT^3} \]

S.W. vanSciver, *Helium Cryogenics*, (1986), Springer
Silver Sinter

Silver has

- Low sound velocity
  \[ v_{He} = 200 \text{m/s} \]
  \[ v_{Ag} = 3600 \text{m/s} \]
  \[ v_{Cu} = 4700 \text{m/s} \]
- Low sintering temperature

HowTo

- Compress silver powder (\( \phi \approx 150 \text{nm} \)) to \(~50\%
- Bake at 250 °C for 1h in 1bar He

\[ \text{Surface area: } 1.9 \text{m}^2/\text{g} \]

\[ R_K = \frac{\Delta T}{Q} = \frac{c}{AT^3} \]
Mixing chamber design

In Theory

In practice
Experimental Setup

Chip holder

CMN thermometer

Coldfinger

Mixing chamber
Hall Bar sample

Pinto 17 wafer

By courtesy of F. Dettwiler and A. Renfer
Landau quantization in a 2DEG

Lorenz force

\[ evB = m^* \omega^2 r \]

\[ \omega_c = \frac{eB}{m^*} \frac{2\pi r_c}{\lambda_F} = n \]

\[ E_n = (n + 1/2) \hbar \omega_c \]
Quantum Hall effect

www.sp.phy.cam.ac.uk/SPWeb/research/QHE.html

R. J. Haug, SST, 8, (1993)
Quantum Hall effect

- Resistance = Energy dissipation = Scattering

→ Shubnikov-de Haas oscillations

\[ R_H = \frac{h}{2e^2} \frac{1}{N} \]

http://www.warwick.ac.uk/~phsbm/2deg.htm

C.W.J. Beenakker et al., SSP; 44, (1994)
Quantum Hall effect

Basic characterization

\[ n = \frac{1}{e \frac{dR_H}{dB}} = 0.97 \times 10^{11} \text{ cm}^{-2} \]

\[ \mu = \frac{1}{n e R_{xx} \frac{W}{L}} = 1.56 \times 10^6 \text{ cm}^2 \text{ Vs} \]

\[ R_\square = 41.2 \Omega \]

Ohmic contacts: 300-1500 \( \Omega \)
Shubnikov-de Haas oscillations

SdH oscillations are broadened by:

- Disorder: \[ \Delta E \gg \hbar / \tau_m \quad \tau_m = \frac{e\mu}{m^*} \]
- Thermal energy: \[ \Delta E \gg k_B T \]

LL splitting: \[ E = \hbar \omega_c \approx 20.5 \frac{K}{T} \]

Zeeman splitting: \[ E = g\mu_B B \approx 290 \frac{mK}{T} \]
Shubnikov-de Haas oscillations

Thermal suppression of SdH oscillations:

In spin valley:

\[ R_{xx} \propto \exp\left(\frac{g\mu_B B}{k_B T}\right) \]

\[ \ln(R_{xx}) \propto \frac{g\mu_B B}{k_B} \frac{1}{T} \]
Electron Temperature

Thermal suppression of SdH oscillations:
In spin valley:

\[
\ln(R_{xx}) = \left(\frac{g\mu_B B}{k_B}\right) \frac{1}{T}
\]

Deviation of linear behaviour:
- Current heating (~50fW)
- Vibrations
- RF noise
- Disorder \((E >> \hbar/\tau_m)\)
Electron Temperature

Thermal suppression of SdH oscillations:
In spin valley:

\[ g = \frac{d \ln(R_{xx})}{d \frac{1}{T}} \frac{k_B}{\mu_B B} \]

<table>
<thead>
<tr>
<th></th>
<th>( g )</th>
<th>( T_e ) [mK]</th>
<th>( T_b ) [mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>#2</td>
<td>0.48 ± 0.13</td>
<td>55 ± 9</td>
<td>22</td>
</tr>
<tr>
<td>#3</td>
<td>0.40 ± 0.14</td>
<td>33 ± 7</td>
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<tr>
<td>#4</td>
<td>0.48 ± 0.07</td>
<td>28 ± 4</td>
<td>15</td>
</tr>
</tbody>
</table>
Quantum Hall effect
Electron Temperature

Thermal suppression of SdH oscillations:
\( v = 5/3 \):

\[ \Delta E = 119 \text{mK} \pm 10 \quad T_e = 44 \text{mK} \pm 3 \]
Earlier Experiments 1

Measurement of electronic temperature first demonstrated in $v=5/2$ state \cite{Gammel1988}.

Sample indium soldered to a magnetic cooling device ($T_{\text{lattice}}<1\text{mK}$) with extensive filtering.

\[ T_e=9\text{mK} \]
Earlier Experiments 2

Measurement of electronic temperature first demonstrated in $v=\frac{5}{2}$ state  


Sample indium soldered to a magnetic cooling device ($T_{\text{lattice}}<1\text{mK}$) with extensive filtering:

- 30Mhz @ RT
- Lossy coax down to 20mK and 6dB point at 20MHz coax thermally clamped at several points
- 10Khz LP-Filter on sample can

$T_e=9\text{mK}$
Earlier Experiments 3

Measurement of electronic temperature in $\nu=5/2$ state
Sample placed in a $^3$He cell attached to the mixing chamber
RF-Filters at 1.2K-plate with cut-off frequency at 10kHz on each wire
$T_e=4\text{mK}$ and $T_b=2\text{mK}$

J.S. Xia et al., *Physica B*, **280** (2000)
Conclusions

New mixing chamber design with efficient heat exchange
Measurement of electron Temperature in a Hall Bar using
Thermal suppression of SdH oscillations ($T_e \leq 28 \text{mK}$)

Limits are:
Disorder $\leftrightarrow$ finite Resistance
Noise
Vibrations
Resistivity of sample and ohmic contacts
Outlook

Adiabatic demagnetization stage
→ Cooling to even lower T by Magnetic cooling

Find new Physics, like
• New FQH states
• Less scattering ↔ longer coherence
• New Quantum phase transitions
•
•
Magnetic cooling 1

Copper: Nuclear Spin 3/2

\[ S = Nk_B \left( \ln(4) - \frac{5g_N^2 \mu_N^2 B^2}{4k_B T^2} \right) \]

http://www.lancs.ac.uk/depts/spc/research/condmatt/ult/demag.htm
Magnetic cooling 2

\[ S = N k_B \left( \ln(4) - \frac{5g_N^2 \mu_N^2 B^2}{4k_B T^2} \right) \propto \frac{B^2}{T^2} \]

G. Pickett, RPP, 51, (1988)

E. Brueck, JPD, 38, (2005)
Thank you!
How to get electrons cold

• “Two Bath model”

• Heat input: \[ dQ = I^2 R \]
  mainly ohmic contacts (R: 300Ω-1.3k Ω)

• Wiedemann-Franz law

\[
\frac{K}{\sigma} = LT \quad L = 2.44 \times 10^{-8} W \Omega K^{-2}
\]

\[
R_{Ohmic,Th} \approx 4.1 \times 10^{11} K / W \quad (R_{el} = 100Ω; 10mK)
\]

\[
R_K \approx 2 \times 10^4 Kg / W \quad \text{A. deWaard, PHD Thesis, (2003)}
\]

\[
R = R_{Th} + R_K
\]

\[
LT = \frac{\sigma}{\kappa} 10^{10} \quad (10/1.411)
\]

\[
R(I \frac{dQ}{dt})^2 = W K / R_K
\]

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A.K.M. \ Wennberg \ et \ al. \ PRB, \ 34, \ (1986)
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W. \ Pan \ et \ al. \ Phys. \ E, \ 6, \ (2000)
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