Progress towards an electronic array on liquid helium

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Beginnings: Single Electron Control

Royal Holloway
G. Papageorgiou, P. Glasson et al
APL 86, 153106 (2005)

Courtesy of Dr. Yury Mukharsky and Emmanuel Rousseau at CEA at Saclay, France
Aims of New Device

• Single electron manipulation and detection
  • Array of electron traps
  • Trap-to-trap control and manipulation
  • Stark shift tuning (Individual trap)
• Collect electrons in an electron reservoir
  • Apply microwaves ~ 200 GHz
New Device Designs

Multi-Trap Electron Array

- Electron storage
- SET as an electron detector
- Multi-trap sample
- Single trap Stark shift tuneable

Reservoir

4 µm
New Fabricated Device

SET (1)

Traps

2

3

4
SET \( I-V \) Curve

Single Electron Transistor
Current vs Ei as Voltage vs Gate Voltage
Device SET $I-V$ Curve

Single Electron Transistor
Current vs Bias Voltage vs Gate Voltage
Coulomb Blockade Oscillations (CBO)
Double-Island SET

Double-Island?

Unusual current peaks with $V_g$ modulation are observed!

Current peak positions are predicted by assuming 2 SET islands capacitively coupled.

Structure reproduced by Lorentzian fit about each peak position.

However, SET is still charge sensitive!

Noise predicted
Phase Shift Due to Adding Helium

$\Delta_{\text{He}} = 0.58 \mu m$
predicts a 0.92% change in period.

Simulated Capacitance shift with He depth

Channel height
~0.58 \mu m

4He

$\varepsilon_{\text{He}}$

Reservoir

SET

4 \mu m

I

$V_{\text{reservoir}}$

0.98%
Phase Stability Before Adding Electrons

Before charging:
Stable phase over 600 mV range
After Charging:

- Decrease in period
- Changes in phase observed


- Phase change accrues in discreet jumps
- Jumps in ‘Trap Charging’ direction
- Charge movement detected.
- Charge increase in jumps.
- Well charging direction
- Can follow hysteretic charge/discharge loop with reservoir electrode sweep
- However charge movement quickly ceases!
With all electrodes held at constant potential we can sweep the SET potential negative with respect to the well.

Observe many discharging events even at highly negative voltage.

Strong indication that our well is too deep…
Conclusions about Multi-Trap Sample I

- Charge stable before firing.
- SET is sensitive to charge movement.
- Trap area can be charged.
- Inability to discharge well indicates sample problems
Fabrication, Problems
& Muti-Trap II

David Rees
Fabrication - Linear trap array design

Require linear array of potential wells:

Ideally… \(V_{\text{well}} \sim 3 \text{ mV}\)

\(d \leq 1.5 \text{ µm}\)

\(h \sim 0.5 \text{ µm}\)

DiVincenzo and Loss (PRA 57, 120 (1998))
Modelling of linear trap array

\[ d = 1.4 \, \mu\text{m} \]

\[ V_{\text{well}} \approx 3\text{mV} \]

\[ f_0 = 21.3 \, \text{GHz} \]
Reservoir

Guard (75nm Au)

SET
Problems – charge loss

Can follow hysteretic charge/discharge loop with reservoir electrode sweep

However charge movement quickly ceases!
Electrons may drain through spikes in reservoir electrode

OR

Bending of He film under electrostatic pressure may cause short
An electrostatic potential (contact potential) develops when two materials of different work functions \( \varphi \) are brought into contact:

\[
V_{cp} = - (\varphi_B - \varphi_A)/e
\]

\( \varphi_{Au} \approx 5.1eV, \varphi_{Al} \approx 4.1eV \)

For Al/Au: \( V_{cp} \approx 1V \) (!)
Problems – Au/Al contact potential

φ of Al/Au sample measured by KP Technology (Prof. Iain Baikie) via scanning electrostatic probe technique:

$V_{cp, measured} = 1074 \pm 141 \text{ mV}$

$\phi_{Ag} \approx 4.7\text{ eV}$

$\phi_{Nb} \approx 4.3\text{ eV}$
We have modified our sample design – fabrication is currently underway firstly in Au and ultimately in Nb!

Split reservoir to observe change in $C_{RES1}$
The Microwave System and Cell

Prof. Mike Lea
Microwaves for Qubits on Helium

Peter Frayne
Royal Holloway
University of London

Rydberg resonance
190 GHz
$E_z = 10.7$ kV/m

Tuning
Reference
Cavity

Gunn Oscillator
Isolator
Amplifier
Attenuator
PIN modulator
Frequency Doubler

WR10 Waveguide
Mode transformer
Mechanical Chopper
300 Hz

2 ns risetime
180 ± 15 GHz
5 mW

WR5 WR28 SS

Cryostat

90 ± 7.5 GHz
30 mW
Phase locked to 10 MHz

+ 7dB

Reference Cavity

Tuning

Frequency
Doubler
Microwaves for Qubits on Helium

Peter Frayne
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Microwave System 2

Mylar window + In O-ring

Bandpass Filter
Δf = 1 GHz
1 dB loss

Options
• Thermal filter
• Thermal break

WR28 SS

WR 5

4.2 K

1.3 K

0.6 K

0.1 K

Fundamental Waveguide
WR 5

Glass/metal seal

WR28 SS

Cell

Tuning

Chip
Microwaves for Qubits on Helium

Thermal break in fundamental mode waveguide - two back-to-back waveguide tapers (WR-05 to WR-28) with needle point mountings

Band-pass filter (WR-05) for removing thermal radiation complete with coupling horns to overmoded waveguide (WR-28)

Fundamental mode 'Swan-Neck' coupling piece for microwave cell

Upper microwave cell showing waveguide and coupling pin
Low Microwave Power
• Stark tuning resonance $f_{12}(E_z)$
• Linewidth $\gamma(T)$
• Temperature dependent resonance $f_{12}(T)$

High Microwave Power
• Absorption saturation
• Power broadening
• Absorption hysteresis
Electrons on Bulk Helium

Microwave inter-subband absorption

CW microwaves (165 GHz - 220 GHz)

Sweep DC

Modulation AC

1 kHz

Lock-in

Electrodes

Putley detector (InSb bolometer)

Cell

Waveguide

Cell

Electrons on Bulk Helium

Microwave inter-subband absorption

CW microwaves (165 GHz - 220 GHz)

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Cell

Waveguide
Ground state to first excited Rydberg state

Resonant frequency $f_{12}$ increases with $E_z$

- **Theory**: $5.06 \text{ GHz/(kV/m)}$
- **189.6 GHz**
- **10.7 kV/m**
- **Our results**
- Brown, Grimes, Zipfel, 1976

1.5 K
Low power

Electrons on Bulk Helium
High temperatures:
Lorentzian broadening

Resonance frequency decreases as the temperature increases
Temperature dependent linewidth

Electrons on Bulk Helium

Theory: Ando (1976)

\[ \gamma(T) = AT + BN_{gas} \]

Ripplon Gas atom Scattering

NB not the absolute linewidth

Inhomogeneous broadening plus a contribution \( \gamma(T) \)

Grimes et al. (1976)

E. Collin et al. PRL 89, 245301 (2002)
\[ \Delta f_{12} (T) = f_{12} (0) - f_{12} (T) \approx 800 \text{ MHz at } 1 \text{ K} \]

\[ \Delta f_{12} (T) \propto T^{5/2} \text{ or } \propto T^{7/3} \]

\( f_{12} = 189.6 \text{ GHz} \)

- \( T \)-dependent surface profile and potential well
- 2-ripplon effects?
Absorption Saturation + Power Broadening

Electrons on Bulk Helium

Absorption

Microwaves

Emission

2-level system?

Rabi frequency $\Omega$

$\Omega^2 \propto$ Power

$\rho_1$

Decay time $\tau = T_1$

$\rho_0$

$\alpha = \frac{0.5 N \gamma \Omega^2}{\delta^2 + \gamma^2 + \gamma \tau \Omega^2}$

BUT:

Heating?

Higher sub-bands?

Bleaching?

$\gamma_P^2 = \gamma^2 + \gamma \tau \Omega^2$
Vertical transitions:
Microwave absorption: $1 \rightarrow 2$
Energy relaxation: $\tau_E$: $N \rightarrow 2 \rightarrow 1$
(2-ripplon)

Horizontal transitions:
Momentum scattering: $\tau_k$: $N \leftrightarrow 2 \leftrightarrow 1$
(1-ripplon + gas atom)

Thermal equilibrium
Electron-electron scattering: $\tau_{ee}$

Microwave energy $\rightarrow$ Very hot electrons $\rightarrow$ Excited sub-bands
$\rightarrow$ Bleaching + Population saturation
$\rightarrow$ Power broadening + Absorption saturation
Electrons on Bulk Helium

Coulomb Non-linearity

\[ \Delta f_{12} = \frac{e^2 \Delta z^2}{h \, 4\pi \varepsilon_0 a^3} \]

Resonance frequency shifts with
- Electron density
- Power absorbed
  (excited state population)

\[ \Delta f_{12} \approx 34 \text{ MHz} \]
\[ n = 10^{11} \text{ m}^{-2} \]
2-level saturation

Finite a.c. voltage modulation
Electrons on Bulk Helium

Hysteresis \equiv Complex Lineshape

\[ T = 0.9 \, \text{K} \]

\[ T = 0.5 \, \text{K} \]
Low Microwave Power
• Stark tuning resonance $f_{12}(E_z)$
• Linewidth $\gamma(T)$
• Temperature dependent resonance $f_{12}(T)$

High Microwave Power
• Absorption saturation
• Power broadening
• Absorption hysteresis
Future Setup
RF Set

Dr. Vladimir Antonov