Coulomb Blockade Thermometer: a primary device for sub-kelvin measurements

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• CBT: the operation principle
• Challenges: $E_C$; background; homogeneity
• Fabrication for high $T > 4K >$ low $T$ sensor
• Sensor performance

$$T_{CBT} = \frac{eV_{1/2}}{5.439Nk_B}$$
Labaratory

- wire bonder etc..
- 4 small dilution refrigerators $T \sim 30\,\text{mK}$
- one „dry“ cryostate for high frequency measurements,
Research environment

OtaNano

Low Temperature Laboratory

- 2600 m² cleanroom (ISO 4 to ISO 6)
- jointly run by VTT Technical Research Centre of Finland and Aalto University
- open access facility
- Electron beam lithography
  Vistec EPGS 5000+ (2014)
- RIEOxfordPlasmaLab80Plus
- ALD reactors (Beneq, Picosun)
- Thin film deposition e-beam, thermal, sputter
- Mask aligner, Laserwriter
- sputter, FIB, SEM, ...
UNCERTAINTY COMPONENTS AND TRACEABILITY OF COULOMB BLOCKADE THERMOMETRY

• below 1 K: Provisional Low Temperature Scale of 2000, PLTS-2000

• proposed kelvin redefinition in terms of the Boltzmann constant ($k_B$)

• Implementing the new kelvin InK (2) => need for primary thermometry methods

results with different methods, check of consistency
$E_C \ll k_B T$

Thermometry by Arrays of Tunnel Junctions

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(Received 13 July 1994)
CBT: Coulomb Blockade Thermometer

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\[ E_C \ll k_B T \]

\[
T_{CBT} = \frac{eV_{1/2}}{5.439Nk_B}
\]

\[
\Delta G/G_T = \frac{1}{6k_B T} \frac{E_C}{k_B T}
\]
CBT: Coulomb Blockade Thermometer

Challenges: Ec, high T (homogeneity, background) low T, (thermalisation)
Coulomb Blockade: charging energy $E_C$

$T \frac{E_c}{k_B}$

<table>
<thead>
<tr>
<th>$T$ (K)</th>
<th>$E_c$ (k$_B$)</th>
<th>size (nm)</th>
<th>Fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>$10^2$</td>
<td>1</td>
<td>?</td>
</tr>
<tr>
<td>10</td>
<td>$10^1$</td>
<td>10</td>
<td>EBL</td>
</tr>
<tr>
<td>1</td>
<td>$10^0$</td>
<td>100</td>
<td>Optical/EBL</td>
</tr>
<tr>
<td>100 mK</td>
<td>$10^{-1}$</td>
<td>1</td>
<td>Optical mask</td>
</tr>
<tr>
<td>10 mK</td>
<td>$10^{-2}$</td>
<td>10</td>
<td>Optical mask</td>
</tr>
</tbody>
</table>

A. V. Feshchenko, M. Meschke, D. Gunnarsson, M. Prunnila, L. Roschier, J. S. Penttilä and J. P. Pekola

Primary thermometry in the intermediate Coulomb blockade regime

Fabrication with tri-layer resist scheme

Germanium mask

45 nm x 32 nm

77 x 30 junction array; Evaporation rate > 1 nm/s
Fabrication with tri layer resist scheme

Germanium mask, 45 nm x 32 nm junction size

<table>
<thead>
<tr>
<th>Junction</th>
<th>Array 1 kΩ</th>
<th>Array 2 kΩ</th>
<th>Array 3 kΩ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>78</td>
<td>93</td>
<td>74.0</td>
</tr>
<tr>
<td>2</td>
<td>71</td>
<td>92.5</td>
<td>69.5</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>85</td>
<td>64</td>
</tr>
<tr>
<td>4</td>
<td>72</td>
<td>89.5</td>
<td>68.9</td>
</tr>
<tr>
<td>5</td>
<td>74</td>
<td>--</td>
<td>70.9</td>
</tr>
<tr>
<td>6</td>
<td>89</td>
<td>92</td>
<td>70.2</td>
</tr>
<tr>
<td>7</td>
<td>94</td>
<td>92</td>
<td>68</td>
</tr>
<tr>
<td>8</td>
<td>99</td>
<td>103</td>
<td>72</td>
</tr>
<tr>
<td>9</td>
<td>76</td>
<td>107</td>
<td>68</td>
</tr>
<tr>
<td>10</td>
<td>87</td>
<td>96</td>
<td>68</td>
</tr>
<tr>
<td>11</td>
<td>78</td>
<td>88</td>
<td>75.6</td>
</tr>
<tr>
<td>Mean, kΩ</td>
<td>81.6</td>
<td>93.8</td>
<td>70</td>
</tr>
<tr>
<td>standard deviation, kΩ</td>
<td>9.3</td>
<td>6.7</td>
<td>3.3</td>
</tr>
<tr>
<td>relative deviation,</td>
<td>11.4 %</td>
<td>7.2 %</td>
<td>4.7 %</td>
</tr>
<tr>
<td>Resulting temperature deviation</td>
<td>-0.7 %</td>
<td>-0.25 %</td>
<td>-0.07 %</td>
</tr>
</tbody>
</table>

\[ T = 4.38(5) \text{ K} \]
CBT setup: compare 3 sensors

$V_{\text{BIAS}/\text{Junction}}$

$\text{DG/ST}$

$4.2\text{K}$

$\text{Ec/kB} = 11\text{ K}$
CBT & background correction

\[ \Delta G/G \]

\[ V_{BIAS}/Junction \]

\[ T = 9K \]

Graph showing the relationship between \( V_{BIAS}/Junction \) and \( \Delta G/G \) for different CBTs at a temperature of 9K.
CBT & background correction

- Fit [-30 mV/J .. 30 mV/J]
- Background correction $R(1 + aV^b)$ $b = 6$
homogeneity of CBT for T>10 K

M. Meschke, O.M. Hahtela, A. Kemppinen, A. Manninen, M. Heinonen, J.P. Pekola

Fabrication with suspended germanium mask:
- Good resolution => high $E_C$ (>10 K)
- Homogeneity of $R_T$ (~ 5%) for absolute T accuracy of ~ 0.5%

3 sensors agree within 0.2 % (relative deviation) ⇒ <10 % scatter in $R_T$
Voltage gain of 100 required for SJT!
SJT vs. CBT at T optimum

Direct voltage measurement,
No amplification needed
(77 Junctions)

⇒ 1e-4
⇒ Limit homogeneity < 1e-2

Voltage gain of 100 required for SJT!
⇒ 1e-2
Tunnel junction process for CBTs

M. Prunnila, M. Meschke, D. Gunnarsson, S. Enouz-Vedrenne, J. M. Kivioja, and J.P. Pekola

Fabrication of Low Temperature CBTs

Nanoelectronic primary thermometry below 4 mK

Nature Communications 7, 10455 (2016)
Characterisation of Low Temperature CBTs

New evaluation of $T - T_{2000}$ from 0.02 K to 1 K by independent thermodynamic methods

J. Engert, et al. proceedings of Tempmekko 2016 (InK)
Coulomb Blockade Thermometer: a primary device for (sub)-kelvin measurements

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2 Centre for Metrology and Accreditation (MIKES), Finland
3 VTT Technical Research Centre, Finland

- Robust temperature range 10 mK .. 10 K
- Primary + self diagnostic
- Accurate (1% total accuracy)
- Simple voltage measurement
- Robust (ESD, radiation, magnet field (20 Tesla)