Springer Theses
Recognizing Outstanding Ph.D. Research

Alexander Thomas Jones

Cooling Electrons in Nanoelectronic Devices by On-Chip Demagnetisation

Springer

Springer Theses

Recognizing Outstanding Ph.D. Research

Aims and Scope

The series "Springer Theses" brings together a selection of the very best Ph.D. theses from around the world and across the physical sciences. Nominated and endorsed by two recognized specialists, each published volume has been selected for its scientific excellence and the high impact of its contents for the pertinent field of research. For greater accessibility to non-specialists, the published versions include an extended introduction, as well as a foreword by the student's supervisor, explaining the special relevance of the work for the field. As a whole, the series will provide a valuable resource both for newcomers to the research fields described, and for other scientists seeking detailed background information on special questions. Finally, it provides an accredited documentation of the valuable contributions made by today's younger generation of scientists.

Theses are accepted into the series by invited nomination only and must fulfill all of the following criteria

- They must be written in good English.
- The topic should fall within the confines of Chemistry, Physics, Earth Sciences, Engineering and related interdisciplinary fields such as Materials, Nanoscience, Chemical Engineering, Complex Systems and Biophysics.
- The work reported in the thesis must represent a significant scientific advance.
- If the thesis includes previously published material, permission to reproduce this must be gained from the respective copyright holder.
- They must have been examined and passed during the 12 months prior to nomination.
- Each thesis should include a foreword by the supervisor outlining the significance of its content.
- The theses should have a clearly defined structure including an introduction accessible to scientists not expert in that particular field.

More information about this series at http://www.springer.com/series/8790

Alexander Thomas Jones

Cooling Electrons in Nanoelectronic Devices by On-Chip Demagnetisation

Doctoral Thesis accepted by
Lancaster University, Lancaster, United
Kingdom

Springer

Author
Dr. Alexander Thomas Jones
Department of Physics
Lancaster University
Lancaster, UK

Supervisor
Dr. Jonathan R. Prance
Department of Physics
Lancaster University
Lancaster, UK

ISSN 2190-5053 ISSN 2190-5061 (electronic)
Springer Theses
ISBN 978-3-030-51232-3 ISBN 978-3-030-51233-0 (eBook)
https://doi.org/10.1007/978-3-030-51233-0

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Supervisor's Foreword

I am pleased to introduce this excellent thesis by Alex Jones. It addresses a long-standing problem in low temperature physics: how to cool very small electronic devices to ultra-low temperatures. Alex has demonstrated a new approach in which demagnetisation refrigeration of on-chip refrigerant is used to cool electronic devices significantly below the temperature of their surroundings. This thesis describes the physical mechanisms of cooling and thermometry, the design of suitable electronic devices and experimental demonstrations of the technique.

Low temperature electronic measurements of micro and nanoscale devices underpin many areas of contemporary condensed matter physics. Research topics from strongly correlated electron systems to quantum technologies rely on ready access to millikelvin temperatures. It is relatively straightforward to cool an electronic device, circuit or material to ~ 0.1 K using a dilution refrigerator. However, at lower temperatures, it becomes increasingly challenging to make a good thermal connection between the coldest part of the refrigerator and the conduction electrons in a device. This happens because the couplings between different thermal subsystems inside a material generally weaken at low temperatures. While a dilution refrigerator may be effective at cooling the lattice of a sample (reducing the phonon temperature), it is entirely possible that conduction electrons in the same sample are more strongly coupled to the external wiring than their host lattice. As a result, it is common to find that the electron temperature in a sample is significantly higher than the temperature of the refrigerator. Careful work on electronic filtering and thermalisation is needed to reach electron temperatures below 10 mK.

For the last 15 years or so, the lowest reported on-chip electron temperatures have been stuck around 4 mK. This thesis describes how on-chip demagnetisation refrigeration was used to reach an electron temperature of 1.2 mK. Following this, the same technique has been taken up by other research groups and the record low temperature is currently just above 0.4 mK. This rapid progress suggests that the technique has real potential to become a standard tool of low temperature physics. The challenge now is to use on-chip demagnetisation to cool the electrons in an arbitrary sample. In the future, this could be used to improve the performance of existing low temperature technologies, and perhaps to discover new physics in a previously inaccessible regime.

Lancaster, UK
March 2020

Dr. Jonathan R. Prance

Abstract

This thesis describes a novel cooling technique which allows the electrons within nanoelectronic devices to reach new low temperatures: nuclear demagnetisation of copper refrigerant mounted directly onto the chip of a nanoelectronic device. This is within a field which has expanded in interest in recent years, due to the promise of new low electron temperatures allowing the investigation of new physical phenomena, the better fidelity of fundamental quantum effects and the improvement in quantum technologies such as quantum computers and sensors. Throughout the study, the effectiveness of the new technique is verified by applying it to a Coulomb Blockade Thermometer (CBT), a nanoelectronic device which provides primary (accurate without any need for calibration) thermometry of its own internal electron temperature. This thesis follows the development of this technique, starting from the initial proof of concept measurements made using a commercial, cryogen free, dilution refrigerator, as would be found in many low temperature and quantum transport laboratories. Here, the device electrons were cooled from 7 mK, the base temperature of the dilution refrigerator, to 4.5 mK without using any other elaborate experimental constructions, opening the technique up to many other laboratories. This technique was then furthered by applying it to a newly adapted CBT which has the lowest operation temperature capability yet reported of $\approx$300 μK. This was done in a dilution refrigerator custom built in Lancaster, resulting in a minimum electron temperature of 1.20 ± 0.03 mK. This has opened the door to a new temperature regime to study new quantum effects, and going forward this technique will, therefore, be applied to other devices in order to enable these further investigations.

Acknowledgements

All three Coulomb Blockade Thermometers (CBTs) used in this study were designed and fabricated by K. Grigoras, D. Gunnarsson, H. Heikkinen and M. Prunnila at VTT, the Technical Research Centre of Finland, and by J. Penttilä and L. Roschier at Aivon Oy. The original, unmodified version of the code which describes a full tunnelling model of a CBT is from the open source project pyCBT, developed by J. Penttilä and L. Roschier at Aivon Oy.

Throughout the writing of this thesis, and the measurements that went into it, I am very grateful to have been supported by a fantastic team of people. Special thanks must, of course, go to my supervisors, Yuri Pashkin and Jon Prance, who have provided invaluable support, guidance and advice throughout, from the initial set-up of the experiment all the way to proof reading this thesis.

Credit for making the brilliant current sources used for all the measurements must go to Stephen Holt and his team in the Lancaster Physics Electronic Workshop, and credit for making the many precise bits and pieces that held everything together must go to Alan Stokes and Martin Ward in the Ultra-Low Temperature Workshop. Dilution refrigerators are complex beasts, and I must thank Jon Prance for help with running the dry dilution refrigerator, Ian Bradley and Roch Shanen for help with Fridge 6, and Dima Zmeev and Samuli Autti for help with Fridge 4.

The lab has been a brilliant place to work, mainly because of all the great people within it who were always willing to help at the drop of a hat. As well as those above, I thank Rich Haley for his brilliant way with words, shielding me from much of the bureaucracy, and for introducing me to the lab one summer 6 years ago. I thank Tony Guénault for his helpful advice throughout the experiments. Thanks to Andy Guthrie, Josh Chawner and Theo Noble for always being available to be grabbed when I quickly needed assistance.

Outside the lab, thanks to my many customers of coffee club (some of whom I still don't know), for giving me an excuse to step back and do something simple from time to time. Last, but not least, thank you to my friends here, past and present, and too many to list, who made my time so enjoyable with lunch time games, discussions about anything and everything, and trips to the pub, cinema and countryside.

Contents