14

Some Comments on Low-Temperature Electronics

There are low-temperature experiments that require electronics kept at low temperatures, sometimes even kept at millikelvin temperatures – the reason being mostly that the electrical noise level at a low-temperature experiment in a properly designed cryostat usually is much smaller than at the room temperature environment. Hence, when weak signals have to be transferred from a low-temperature experiment to electronics at room temperature the signal has to be amplified at low temperatures requiring electronics that work at these temperatures. The use of low-temperature electronics in general gives a substantial improvement in sensitivity and in the signal-to-noise ratio. The other situation requiring low-temperature electronics occurs when the electronic device itself can only be operated at low temperatures, like a SQUID. It surely would increase the volume of this book too much if I would include an adequate discussion of low-temperature electronics. Hence, I will only give a survey on recent relevant literature rather than discussing cryo-electronics in detail.

Fortunately, one can find good recent books, review articles, and comprehensive original articles on cold electronics in the literature. For example, the book "Low Temperature Electronics: Physics, Devices, Circuits, and Applications" with close to 2,000 relevant references [14.1]. It covers the range from room temperature to millikelvin temperatures. A good overview of its content is given by the chapter titles: Physics of Silicon at Cryogenic Temperatures; Silicon Devices and Circuits; Reliability Aspects of Cryogenic Silicon Technologies; Radiation Effects and Low Frequency Noise in Silicon Technologies; Heterostructure and Compound Semiconductor Devices; Compound Heterostructure Semiconductor Lasers and Photodiodes; High Temperature Superconductor/Semiconductor Hybrid Devices and Circuits; Cryocooling and Thermal Management. The book deals among others with silicon metal-oxide-semiconductor(MOS) bulk transistors, silicon-on-insulator MOS transistors, gallium arsenide field effect transistors (FETs), silicon and gallium arsenide MOSFETs, silicon germanium bipolar transistors, resonant tunneling diodes, optical and optoelectronic devices, quantum well (QW) and

F. Pobell, *Matter and Methods at Low Temperatures*

strained-layer QW lasers, double-heterostructure lasers, indium phosphide/ indium gallium arsenide avalanche photodiodes, QW infrared photodiodes, as well as microwave filters, antennas, and oscillators which became particular attractive with the advancement of high-T_c-superconductors.

A rather attractive design of a low-noise, low-power, three-stage amplifier based on high-electron-mobility transistors assembled on a printed board of $33 \times 13\,\mathrm{mm}^2$ has been described in [14.2]. It has a minimum noise temperature of about 0.1 K at an ambient temperature of 0.38 K at frequencies between 1 and 4 MHz, with a corner frequency of the $1/f$ noise close to 300 kHz. Its gain is 50 at a power of 0.2 mW. Another rather promising cryogenic 700-MHz low-noise (3 K) amplifier with a gain of 16 dB operated at 4.2 K has been described in [14.3].

Surely, the most important cryo-electronic device is the extremely sensitive superconducting quantum interference device ("SQUID"). A SQUID is essentially a closed superconducting loop containing one or several weak links ("Josephson junctions"). Into this loop magnetic flux is frozen in. The frozen-in flux is changed stepwise in units of the flux quantum each time the small critical current I_c of the weak link is reached by shielding currents in response to an external magnetic field. The small size of the flux quantum $\Phi_o = h/2e = 2 \times 10^{-11}\,\mathrm{T\,cm}^2$ and the possibility to measure even 10^{-5} Φ_o in 1-Hz bandwidth give the SQUID its enormous sensitivity in a measurement with negligible dissipation. The various versions of the SQUID, like DC- and RF-SQUIDs have been developed to a very high sophistication both by the research community as well as by industry. A DC-SQUID, for example, contains two Josephson junctions. It is typically biased with a current $I_{\mathrm{bias}} > 2I_c$ so that a voltage V develops across them (I_c: the critical current of one Josephson junction). The voltage is a periodic function of the magnetic flux externally applied to the SQUID ring. The DC-SQUID therefore is operated as a flux-to-voltage converter where voltages of order of several 10 μV are produced by magnetic flux changes as small as a fraction of the flux quantum Φ_o. The flux can be applied by injecting a current in an input coil close to the SQUID ring.

SQUIDs measure first of all weak magnetic fields as flux changes, but with appropriate circuitry also current, voltage, or frequency. The most important applications of SQUIDs in low-temperature physics are for magnetometry (see Sect. 3.4.2), in low-frequency NMR experiments (see Sect. 12.10), and for various types of thermometry, in particular noise thermometry (see Sect.12.7).

A good and detailed description of the fundamentals of the SQUID as well as its applications in low-temperature physics can be found already in Lounasmaa's book [14.4]. Many practical details are described in [14.5]. Review articles or books on the subject are [14.6–14.8]. Fortunately, the long overdue comprehensive modern treatment of SQUIDs and their various applications has been published recently in the two volumes "The SQUID Handbook" by Clarke and Braginski [14.9]. The authors treat in a comprehensive and coordinated presentation the device fundamentals, design, technology, system construction, and many applications of this extremely sensitive device, thus bridging the gap between fundamentals and applications.

There are, of course, various further review and comprehensive original articles on SQUIDs and their applications in the literature. For example, the review on "Superconducting Electronics at mK Temperatures", which treats the development of new SQUID type devices [14.10]. Theory and use of thin-film DC resistive SQUIDs for the temperature range of 12 mK to 5.9 K, in particular for application in noise thermometry (Sect. 12.7) have been described in detail in [14.11]. Low-T_c as well as high-T_c SQUIDs and well-developed, fast SQUID electronics for bandwidth up to 20 MHz described in [14.12] are available commercially. One can also consult various conference proceedings, like for the "SQUID" meetings, or the "Applied Superconductivity Conferences", or the publications in "IEEE Transactions on Applied Superconductivity". And last but not least, many of the advancements have been published in the journals "Review of Scientific Instruments" and "Journal of Low Temperature Physics".

List of Symbols

In some cases – when there is no danger of confusion – the same symbol is used for different purposes; they are separated by a slash in the following list. In the text the symbols are usually explained when they appear for the first time.

A	Area/amplitude
AC	Alternating current
a	Interatomic distance
B	Magnetic field
b	Internal magnetic field
C	Heat capacity/specific heat/capacitance
Db	Decibel
DC	Direct current
d	Distance/diameter/thickness
$E; \epsilon; E_C; E_F$	Energy/Coulomb energy/Fermi energy
e	Elementary charge ($4.803 \times 10^{-10}\,\mathrm{g}^{1/2}\,\mathrm{cm}^{3/2}\,\mathrm{s}^{-1}$; $1.602 \times 10^{-19}\,\mathrm{C}$)
F	Force
f	Distribution function/frequency
G	Shear modulus/differential conductance
g	Density of states/g-factor/acceleration due to gravity ($9.807\,\mathrm{m\,s}^{-2}$)
g_n	Nuclear g-factor
H	Enthalpy/Hamiltonian
h	Height/hour
h; $\hbar = h/2\pi$	Planck constant ($6.626 \times 10^{-27}\mathrm{erg\,s}; 1.055 \times 10^{-27}\mathrm{erg\,s}$)
I	Nuclear spin/moment of inertia
J	Rotational quantum number/total angular momentum quantum number/Joule
k	Rate constant, spring constant
k_B	Boltzmann constant ($1.38065 \times 10^{-16}\mathrm{erg\,K}^{-1}$; $1.38065 \times 10^{-23}\mathrm{J\,K}^{-1}$)

L	Latent heat of vaporization/orbital angular momentum quantum number/length/induction
L_0	Lorenz number (2.45×10^{-8}W Ω/K^{-2})
l	Length
M	Magnetization
m	Mass/magnetic quantum number/magnetic moment/Poisson ratio
m^*	Effective mass
m_e	Electron mass (9.109×10^{-28} g)
N	Demagnetization factor/Newton
N_0	Avogadro number (6.02214×10^{23} atoms mol^{-1})
n	Number of moles or particles/occupation number
P	Pressure/polarization/heat energy, quantity of heat
P_m	Melting pressure
P_{vp}	Vapor pressure
$\bar{P}$	Density of tunneling states in glasses
P_{sat}	Saturated vapor pressure
ppm	Parts per million (10^{-6})
Q	Quantity of heat/nuclear electric quadrupole moment/quality factor
R	Radius/distance/gas constant (8.135 J mol^{-1} K^{-1})/resistance
R_K	Thermal boundary (Kapitza) resistance
RRR	Residual resistivity ratio
RF	Radio frequency
r	Radius/distance
S	Entropy/spin quantum number
T; T_F	Temperature/Fermi temperature
T_c	Critical temperature
T_e	Temperature of electrons
T_n	Temperature of nuclei
T_p	Temperature of phonons
t	Time
U	Internal energy
V	Voltage/Potential/volume
V_m	Molar volume (for a gas: $V_m = 22,414\,cm^3\,mol^{-1}$)
V_{zz}	Electric field gradient ($\delta^2 V/\delta z^2$)
v	Velocity (of sound)
v_F	Fermi velocity
X_{min}	Minimum value of X
x	Concentration
Z	Charge/partition function/impedance
α	Polarizibility/van der Waals constant/thermal expansion coefficient
β	Coefficient of lattice specific heat
γ	Sommerfeld constant of electronic specific heat/gyromagnetic ratio
δ	Skin depth
ΔE	Energy gap

ϵ	Dielectric constant/elastic stress
ϕ_0	Flux quantum ($h/2e = 2.0678 \times 10^{-15}$ V s $= 2.0678 \times 10^{-11}$ T cm^{-2})
η	Viscosity
θ	Moment of inertia/angle/Weiss constant
θ_D	Debye temperature
κ	Thermal conductivity/Korringa constant/torsion, spring constant
λ	Mean free path/Curie constant
ν	Frequency
μ	Magnetic moment/permeability/chemical potential
μ_B	Bohr magneton (9.274×10^{-21} erg G^{-1}; 9.274×10^{-24} J T^{-1})
μ_n	Nuclear magneton (5.051×10^{-24} erg G^{-1}; 5.051×10^{-27} J T^{-1})
μ_0	Permeability of vacuum ($4\pi \times 10^{-7}$ V s A^{-1} m^{-1})
μ_r	Relative permeability
π	Osmotic pressure
Φ	Phase
ρ	Electrical resistivity/mass density
σ	Electrical conductivity
τ	Relaxation time
$\tau_{1/2}$	Half-life time
τ_1	Spin–lattice relaxation time
τ_2	Spin–spin relaxation time
τ_2^*	Effective spin decay time
χ	Susceptibility
$\tau; \tau_m$	Torque/magnetic torque
ω	Frequency $\times 2\pi$
ω_D	Debye frequency $\times 2\pi$
Ω	Ohm

Conversion Factors

$1\,\mathrm{T} = 1\,\mathrm{V\,s\,m^{-2}} = 10^4\,\mathrm{G}$
$1\,\mathrm{G} = 1\,\mathrm{g^{1/2}\,s^{-1}\,cm^{-1/2}}$
$1\,\Omega\,\mathrm{cm} = 10^{-11}/9\,\mathrm{s}$
$1\,\mathrm{meV} = k_B \times 11.60\,\mathrm{K}$
$1\,\mathrm{eV} = 1.602 \times 10^{-12}\,\mathrm{erg}$
$1\,\mathrm{W} = 1\,\mathrm{J\,s^{-1}} = 10^7\,\mathrm{erg\,s^{-1}}$
$1\,\mathrm{Pa} = 1\,\mathrm{N\,m^{-2}} = 10\,\mu\mathrm{bar} = 10\,\mathrm{dyne\,cm^{-2}} = 7.501\,\mathrm{mtorr}$
$1\,\mathrm{J/T} = 1\,\mathrm{A\,m^2} = 10^3\,\mathrm{emu}$

Suppliers of Cryogenic Equipment and Materials

I did hesitate for some time to add this list in the new edition of my book because it surely cannot be complete. The items and suppliers chosen are strongly influenced by my own research experience. In addition, they are taken from industrial exhibitions at relevant conferences, from advertisements in relevant journals, and from the annual Buyer's Guide published as a supplement to the annual August issue of Physics Today.

I give the electronic address of the suppliers only. For the full addresses, one can look, for example, into the above-mentioned Buyer's Guide or, of course, into the Internet. To the best of my knowledge, I have listed the manufacturers and not their representatives in the various countries.

Calorimeters

Oxford Instruments; http://www.oxford-instruments.com
Quantum Design; http://www.qdusa.com

Capacitance Bridges and Capacitance Standards

Andeen-Hagerling; http://www.andeen-hagerling.com
Tucker Electronics (used General Radio 1615A bridges); http://www.tucker.com
Quad Tech Inc.; http://www.quadtech.com

Closed-Cycle Refrigerators; Cryocoolers

Advanced Research Systems Inc.; http://www.arscryo.com
Cryo Industries of America; http://www.cryoindustries.com
Cryogenic Ltd; http://www.cryogenic.co.uk

Cryomagnetics Inc.; http://www.cryomagnetics.com
Cryomech Inc.; http://www.cryomech.com
Dryogenic Ltd; http://www.dryogenic.com
Janis Research Comp.; http://www.janis.com
Leybold Vacuum; http://www.leybold.com
Oxford Instruments; http://www.oxford-instruments.com
Polycold Systems Inc.; http://www.polycold.com
Sumitomo Heavy Industries Ltd; http://www.shi.co.jp
Sunpower; http://www.sunpower.com
Suzuki Shokan Co. Inc.; http://www.suzukishokan.co.jp
VeriCold Technologies; http://www.vericold.com

Cryostats for Liquid ^{3}He

Cryogenic Ltd; http://www.cryogenic.co.uk
ICEoxford; http://www.iceoxford.com
IQUANTUM; http://www.iquantum.jp
Janis Research Comp.; http://www.janis.com
Oxford Instruments; http://www.oxford-instruments.com
VeriCold Technologies; http://www.vericold.com

Dewars and Cryostats for Liquid ^{4}He; Transfer Lines

Advanced Research Systems Inc.; http://www.arscryo.com
Andonian Cryogenics Inc.; http://www.andoniancryogenics.com
Cryo Anlagenbau GmbH; http://www.cryoanlagenbau.de
Cryoconcept; http://www.cryoconcept.fr
Cryofab Inc.; http://www.cryofab.com
Cryogenic Ltd; http://www.cryogenic.co.uk
Cryo Industries of America; http://www.cryoindustries.com
CryoVac; http://www.cryovac.de
ICEoxford; http://www.iceoxford.com
International Cryogenics Inc.; http://www.intlcryo.com
Janis Research Comp.; http://www.janis.com
Kadel Engineering Corp.; http://www.kadel.com
Oxford Instruments; http://www.oxford-instruments.com
Pope Scientific Inc.; http://www.popeinc.com (glass dewars)
Precision Cryogenic Systems Inc.; http://www.precisioncryo.com
VeriCold Technologies; http://www.vericold.com

Dilution Refrigerators, ^{3}He–^{4}He

Cryoconcept; http://www.cryoconcept.fr
ICEoxford; http://www.iceoxford.com

Janis Research Comp.; http://www.janis.com
Leiden Cryogenics BV; http://www.leidencryogenics.com
Oxford Instruments; http://www.oxford-instruments.com
Vericold Technologies; http://www.vericold.com

Epoxy, Grease, Varnish

Apiezon Products-M&I Materials Ltd; http://www.apiezon.com
Aremco Products Inc.; http://www.aremco.com
Ciba Specialty Chemicals Inc.; http://www.cibasc.com
Epoxy Technology Inc.; http://www.epotek.com
Emerson and Cumming Inc.; http://www.emersoncuming.com (Stycast)
Furane Plastics Inc.; http://www.plasticstechnology.com (Epibond)
Gen. Electric Corp., Insul. Mat. Dept.; http://www.GEPlastics.com (GE Varnish)
ICEoxford; http://www.iceoxford.com
Lake Shore Cryotronics Inc.; http://www.lakeshore.com
Oxford Instruments; http://www.oxford-instruments.com

Helium-3 Gas

Chemgas; http://www.chemgas.com
Linde Gas; http://www.linde-gas.de
Sigma-Aldrich Co; http://www.sigmaaldrich.com
Oxford Instruments; http://www.oxford-instruments.com
US Services Inc./Icon Services Inc.; http://www.iconservices.com

Inductance Bridges

Leiden Cryogenics BV; http://www.leidencryogenics.com

Liquid-Level Sensors and Controllers

Andonian Cryogenics Inc.; http://www.andoniancryogenics.com
American Magnetics; http://www.americanmagnetics.com
Cryomagnetics Inc.; http://www.cryomagnetics.com
Janis Research Comp.; http://www.janis.com
Lake Shore Cryotronics Inc.; http://www.lakeshore.com
Oxford Instruments; http://www.oxford-instruments.com

Magnetic and Physical Property Measurement Systems/Magnetometers/Susceptometers

ADE Technologies Inc.; http://www.adetech.com
Cryogenic Ltd; http://www.cryogenic.co.uk
Lake Shore Cryotronics Inc.; http://www.lakeshore.com
Quantum Design; http://www.qdusa.com
Tristan Technologies Inc.; http://www.tristantech.com

Magnetic Refrigerators

Dryogenic Ltd; http://www.dryogenic.com
Janis Research Comp.; http://www.janis.com

Magnetic Shielding

Ad-Vance Magnetics; http://www.advancemag.com
Advent Research Materials Ltd; http://www.advent-rm.com
Amuneal Manufacturing Corp.; http://www.amuneal.com
Magnetic Shield Corp.; http://www.magnetic-shield.com
Vakkumschmelze GmbH; http://www.vacuumschmelze.de

Metals, Metal Wires

Advent Research Materials Ltd; http://www.advent-rm.com
Alfa Aesar; http://www.alfa.com
California Fine Wire Comp.; http://www.calfinewire.com
Cooner Wire Co.; http://www.coonerwire.com
Goodfellow Corp.; http://www.goodfellow.com
Indium Corporation of America; http://www.indium.com
Johnson Matthey; http://www.jmei.com
Kawecky Berylco Industries Inc.; http://www.kballoys.com
Leico Industries Inc.; http://www.leicoind.com
Matek GmbH; http://www.matek.com
Oxford Instruments; http://www.oxford-instruments.com
Pelican Wire Comp.; http://www.pelicanwire.com
Sigmund Cohn Corp.; http://www.sigmundcohn.com
Umicore Precious Metals Refining; http://www.preciousmetals.umicore.com
Wieland Werke AG; http://www.wieland.de

Cu

American Smelting and Refining Comp.(ASARCO); http://www.asarco.com
Hitachi Cable Ltd; http://www.Hitachi-cable.co.jp

Cumerio; http://www.cumerio.com
North American Hoganas Inc.; http://www.hoganas.com
Outokumpu Poricopper Oy; http://www.outokumpu.com
Sofilec Division Buisin; http://www.buisin.com

Metal Powders

Alfa Aesar; http://www.alfa.com
Engelhard Corp.; http://www.engelhard.com
Ferro Electronic Material Systems; http://www.ferro.com
Goodfellow Corp.; http://www.goodfellow.com
Ulvac Technologies Inc.; http://www.ulvac-materials.co.jp

Metal Tubes

ICEoxford; http://www.iceoxford.com
Oxford Instruments; http://www.oxford-instruments.com
Precision Tube Co.; http://www.precisiontube.com
Superior Tube Co.; http://www.superiortube.com
Uniform Tubes; http://www.uniformtubes.com

Micropositioning Systems for Cryogenics

Attocube Systems; http://www.attocube.com
Janis Research Comp.; http://www.janis.com

Nuclear Magnetic Resonance Thermometry on ^{195}Pt, Electronics

Picowatt, RV-Elektroniikka OY; http://www.picowatt.fi

Pressure Transducers, and Gauges

BOC Edwards; http://www.bocedwards.com
Gems Sensors; http://www.gems-sensors.co.uk
MKS Instruments Inc.; http://www.mksinst.com
Wallace & Tiernan Co.; http://www.wallace-tiernan.de

Pomeranchuk Cooling Cells

Leiden Cryogenics BV; http://www.leidencryogenics.com

Resistance Bridges/Temperature Controllers (see also "Thermometry")

Cryo-Con Inc.; http://www.cryocon.com
Cryo Industries of America Inc.; http://www.cryoindustries.com
Janis Research Comp.; http://www.janis.com
Lake Shore Cryotronics; http://www.lakeshore.com
Oxford Instruments; http://www.oxford-instruments.com
Picowatt, RV Elektroniikka OY; http://www.picowatt.fi
Yokogawa Corp.; http://www.yokogawa.com

SQUIDs, SQUID Readout Electronics

Applied Physics Systems; http://www.appliedphysics.com
IQUANTUM; http://www.iquantum.jp
Jülicher SQUID GmbH; http://www.jsquid.com
Magnicon GbR; http://www.magnicon.com
Quantum Design; http://www.qdusa.com
Star Cryoelectronics; http://www.starcryo.com
Tristan Technologies Inc.; http://www.tristantech.com
Twente Solid State Technology BV; http://www.tsst.nl

Superconducting Fixed-Point Device

Hightech Developments Leiden; http://www.xs4all.nl/~hdleiden/srd1000

Superconducting Magnets, Superconducting/Vapor Cooled Current Leads, Power Supplies

Accel Instruments GmbH; http://www.accel.de
American Magnetics; http://www.americanmagnetics.com
American Superconductor Corp.; http://www.amsuper.com
Cryogenic Ltd; http://www.cryogenic.co.uk
Cryo Industries of America; http://www.cryoindustries.com
Cryomagnetics Inc.; http://www.cryomagnetics.com
Cryo-Technics; http://www.cryo-technics.de
Janis Research Comp.; http://www.janis.com
Oxford Instruments; http://www.oxford-instruments.com
Scientific Magnetics; http://www.scientificmagnetics.com

Superconducting Wires and Materials

American Superconductor Corp.; http://www.amsuper.com
European Advanced Superconductors; http://www.advancedsupercon.com
Goodfellow Corp.; http://www.goodfellow.com
Hitachi Cable Ltd; http://www.hitachi-cable.co.jp
Oxford Instruments; http://www.oxford-instruments.com
Supercon Inc.; http://www.supercon-wire.com

Thermometers Including the Relevant Electronics/Bridges and Temperature Controllers

Capacitance

Lake Shore Cryotronics Inc.; http://www.lakeshore.com
Oxford Instruments; http://www.oxford-instruments.com

Coulomb blockade

Nanoway Cryoelectronics Ltd; http://www.nanoway.fi

Nuclear Orientation

Oxford Instruments; http://www.oxford-instruments.com

Resistance

Cryogenic Control Systems; http://www.cryocon.com
CryoVac; http://www.cryovac.de
ICEoxford; http://www.iceoxford.com
Lake Shore Cryotronics Inc.; http://www.lakeshore.com
Oxford Instruments; http://www.oxford-instruments.com
Rosemount Inc.; http://www.rosemount.com
Scientific Instruments Inc.; http://www.scientificinstruments.com

Thermocouples

Janis Research Comp.; http://www.janis.com
Lake Shore Cryotronics Inc.; http://www.lakeshore.com
Oxford Instruments; http://www.oxford-instruments.com
Scientific Instruments; http://www.scientificinstruments.com

Valves, Cryogenic

Andonian Cryogenics Inc.; http://www.andoniancryogenics.com
Cryo Industries of America Inc.; http://www.cryoindustries.com
Hoke Inc.; http://www.hoke.com
Precision Cryogenic Systems Inc.; http://www.precisioncryo.com

Windows for Cryogenic Systems

Oxford Instruments; http://www.oxford-instruments.com