Why superconducting electronics?

- Extremely non-linear IV&RT characteristics
- The Josephson effects $I = I_c \sin \varphi$, $\dot{\varphi} = 2eV/\hbar$
- Low noise
- Low loss
- Low dissipation
- Less weight
- High resolution
- High speed $f_c \sim (2e/h)I_c R_N$
- High frequency $f_J = 483$ GHz/mV
- Quantum limited sensitivity
Devices such as
- SIS tunnel junctions
- Josephson junctions
- SQUIDs
- Magnetometers/Gradiometers (fT)
- Hot electron bolometer (HEB) devices
- Transition edge bolometers
- Digital electronics (e.g., RSFQ)

For applications such as
- Microwave
  - Radio astronomy, X-ray astronomy, THz Hilbert spectroscopy
  - Oscillators (GHz-THz) (JJs and FFOs)
  - Filters
- Certification, Standards, Medicine, Geology, NDE
- High resolution instrumentation (pV, pA,...)

For fundamental research
- Transport properties (tunneling, vortices, superconductivity,...)
- Superconductivity (why?, order parameter, pairing state, etc...)
Why *not* superconducting electronics?

- **Cooling and Cryogenics**
  - Additional costs
  - Additional weight
  - Additional vibrations...
  - Additional power requirements

- **Sensitivity could mean saturation**
  - From incoming signals
  - From EMI

- **End user values**
  - If price vs performance gives no advantage
  - If other technologies solves the problem
Applications

- Metrology, Volt standard
- High frequency applications
- Magnetommeters, SQUIDs
- Amplifiers, SQUIDs
- Imaging, MRI, SQUIDs
- Power applications
Metrology:

The volt standard development

\[ V = n \Phi_o f \]
HTS oscillators and Voltage standards...!

Zero-crossing Shapiro steps observed in BSCCO intrinsic Josephson junctions with \( f_{LO} = 760 \) GHz

\( \Phi_0 = \frac{\hbar}{2e} \): Magnetic flux quantum

\( f = 760 \) GHz

\( V_n = 1.57n \) mV

H. B. Wang (RIEC, Tohoku University, Japan: hbwang@riec.tohoku.ac.jp)

Shapiro steps observed up to 2.5 THz and zero-crossing steps up to 2.5 V and 50 K
High frequency applications

- SIS mixers, for radio telescopes
- Hot electron bolometers
- Transition edge sensors, X-ray detectors
- Passive filters for cell phone stations
Radioastronomy

SEST - the Swedish-ESO Submillimetre Telescope in La Silla (Chile). This is a collaboration between the Swedish National Facility for Radio Astronomy (Onsala Space Observatory) and ESO (European South Observatory). The upper frequency limit of SEST is 350 GHz. Courtesy of European South Observatory

http://www.ls.eso.org/lasilla/Telescopes/SEST/SEST.html
High frequency applications

Frequency/wavelength regions for which different front-end technologies are used for low noise receivers

- Molecular rotation/vibration
- Atomic excitation
- Hot electron bolometers
- Schottky
- SIS
- HEMT

mm
THz
State-of-the-art double sideband (DSB) receiver noise temperatures for different technologies. The lowest noise temperature is given by the “quantum limit”, $T = hf/k_B$. 

![Graph showing receiver noise temperature vs. frequency for different mixers: Josephson Nb mixer, Josephson HTS mixer, SIS mixer, HEB mixer, Schottky, HEMT. The lowest noise temperature is marked by the quantum limit, and multiples thereof.](image-url)
Atmospheric transmission
Low transmission through the atmosphere
Herschel Space Observatory
to be launched feb. 2007

Two frequency bands
(Chalmers):

- 6Low: 1.41-1.75 THz
- 6High: 1.62-1.92 THz
- IF: 2.4-4.8 GHZ

369 M€? 500 total?

http://sci.esa.int/first
Integrated Planar Antennas

Double slot antenna  Mixer mount  Spiral antenna

Quasi-optical coupling

HEB chip

Hot Electron Bolometer Mixer

M=65 g

Si lens  Lens bracket

Au antenna  NbN strip

MC2
TES with time-division SQUID multiplexer

1 x 32 SQUID multiplexer

8 pixels of 8 x 8 x-ray array being read out in a 1 x 8 multiplexed column

8 x 8 x-ray array

32 x 40 SCUBA-2 TES array (not yet micromachined)

PTh30, 10:40-12:30, Poster Session IV, SQUIDs/Standards, Thursday, 10/7/03: Design & performance of a time-domain SQUID multiplexer system for read-out of superconducting transition-edge sensors arrays, C.D. Reintsema, et al.
Superconductor Technologies Inc & Conductus

"A KILLER APPLICATION"
Mechanically cooled microcalorimeter EDS detector
- No Liquid Helium or other cryogens
- Resolutions of 15eV @ Al K
- X-ray energy is measured via temperature change on detector
- High energy resolution at low operating temperatures (100 mK)
- Increase in temperature results in change in resistance
- Resistance change measurement with superconducting electronics (SQUID)
- Increase in temp ≈ energy of absorbed photon
- Output is EDS spectra

Spectral data of WSi₂ sample measured under the following conditions: 5kV, 203pA and 60s acquisition time. W and Si can be identified.

Spectral data of TaSi₂ measured under the same conditions as above: 5kV, 203pA and 60s acquisition time.

Joint project of EDAX and Vericold

http://www.vericold.com/

www.edax.com/products/Microanalysis/detectors/special_EDS/Polaris.html
The SQUID

SQUID: Superconductor Quantum Interference Device

The SQUID is a flux-to-voltage transducer

The dc SQUID; (b) I-V characteristics; (c) V vs. $\Phi/\Phi_0$ at constant bias current $I$. 

ITH5, 18:20-19:10, Oral Session VII, Thursday, 10/7/03: SQUIDs: The limit to measurement, J.Gallop.
SQUID applications

- Magnetometers
- Magnetic microscopes
- Non-destructive evaluation NDE
- Geology and prospecting
- pV- and pA-meters
- Biomagnetism, e.g., MEG, MCG, ...
- Medicine and diagnostics
- Low frequency NMR and MRI
SQUID microscope (IBM)

Figure 1
Schematic diagram of our scanning SQUID microscope [16].

Figure 2
(a, b) Expanded views of the sample area; (c) schematic layout of the integrated magnetometer [16].

Figure 3
Optical image of the tip of a SQUID sensor after polishing.
SQUID microscopes for semiconductor industry


Courtesy of IBM Microelectronics
SQUID localization of cracks in rebar on a German highway bridge

Non Destructive Evaluation (NDE)
Non Destructive Evaluation (NDE)

aircraft wheel

www.jsquid.com
Geology and prospecting

ITH4, 17:30-18:20, Oral Session VII, Thursday, 10/7/03:
The impact of SQUIDs on geophysics, C.P. Foley.
SQUID voltage, current amplifiers

Feedback schemes for the SQUID amplifiers

Voltage amplifier

Current amplifier
Low voltage IV-characteristics of another SQUID

Blue curve is data taken with picovoltmeter. Orange curve is data taken with commercial low-noise amplifier (PAR5113).

Best performance of our voltage amplifiers in different configurations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage noise</td>
<td>3.2 pV/√Hz</td>
</tr>
<tr>
<td>Current noise</td>
<td>0.28 pA/√Hz</td>
</tr>
<tr>
<td>Energy sensitivity</td>
<td>1.7 *10^{-22} J</td>
</tr>
<tr>
<td>Noise temperature</td>
<td>10 K</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>300 kHz</td>
</tr>
<tr>
<td>Slew rate ($R_s = 10 \Omega$)</td>
<td>91 mV/s</td>
</tr>
</tbody>
</table>
Medicine, biophysics and chemistry

- Biomagnetism: MEG, MCG, ...

- Biophysics:
  - Diagnostics by magnetic tagging of antibodies
  - Special frequency characteristics, no rinsing

- MRI (Magnetic Resonance Imaging)
  - Low frequency, low noise amplifiers, sc solenoids

- NMR (Nuclear Magnetic Resonance)
  - Low frequency, small fields, sc solenoids

- NQR (Nuclear Quadropole Resonance)
  - Low frequency, low noise amplifiers, sc solenoids
Magnetoencephalogram  MEG


http://www.uth.tmc.edu/clinicalneuro/epilepsy.htm
Installed systems
Real Time Fetal heart Signals at 37th week Measured Using 1th Order Gradiometer in MSR

Pick-up area: 1 cm²
Baseline: 18 cm
Video bandwidth: 0.025 – 90 [Hz]
SNR: 2

This is the first demonstration to record fetal heart signal in real time, using HTS SQUID gradiometer!
Power applications

- Strong magnets for
  - particle accelerators
  - NMR
  - Research
- Small compact generators and motors
  - Submarines, boats, trains
- Power transmission
- Levitating trains
Power applications

- Strong magnets for particle accelerators
  Fermilab Chicago

- Strong magnets for Magnetic resonance imaging
  extremely uniform fields across the subject and extreme stability over time

- 20T magnet
Power applications
Compact motors and generators

In 1995 the Naval Research Laboratory demonstrated a 167 hp motor with high-Tc superconducting coils made from Bi-2223. It was tested at 4.2K and at liquid neon temperature, 28K with 112 hp produced at the higher temperature.

In mid-July, 2001, American Superconductor unveiled a 5000-horsepower motor made with superconducting wire (below). And expects to deliver an even larger 36.5MW HTS ship propulsion motor to the U.S. Navy by September 2006.
Power applications
Levitating trains

• Magnetic-levitation is an application where superconductors perform extremely well. Transport vehicles such as trains can be made to "float" on strong superconducting magnets, virtually eliminating friction between the train and its tracks.
• The Yamanashi Maglev Test Line opened on April 3, 1997. In December 2003, the MLX01 test vehicle attained an incredible speed of 581 kph.
Power applications
Power Transmission
10% to 15% of generated electricity is dissipated in resistive losses in transmission lines

• In the summer of 2001 Pirelli completed installation of three 400-foot HTS cables for Detroit Edison at the Frisbie Substation capable of delivering 100 million watts of power
Worldwide Market for Superconductivity and Market Shares for Low- and High-\(T_c\) Superconductors in M€

- New electronics applications
- New large scale applications
- Total of emerging new businesses
- Research & technology development (RTD)
- Magnetic resonance imaging (MRI)
- Total of RTD & MRI
- Market shares for high-\(T_c\) Superconductors (HTS)
- Market shares for low-\(T_c\) Superconductors (LTS)
- Total Worldwide market
Cryo coolers

Wishes:
- Cheap
- Small
- Invisible
- Efficient
- Reliable
- No vibrations
- Non-magnetic