Evolution of HTS Josephson junction technology and its application in Japan

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Evolution of HTS Josephson junction technology and its application at ISTEC and SUSTERA

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Introduction and Outline

History of ISTEC and SUSTERA

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>Discovery of HTS materials</td>
</tr>
<tr>
<td>1990</td>
<td>ISTEC (International Superconductivity Technology Center)</td>
</tr>
<tr>
<td>1995</td>
<td>1st decade: GB JJ</td>
</tr>
<tr>
<td>1998</td>
<td>2nd decade: Ramp-edge JJ (IEJ)</td>
</tr>
<tr>
<td>2000</td>
<td>HTS-SFQ devices</td>
</tr>
<tr>
<td>2005</td>
<td>Ramp-edge JJ (modified)</td>
</tr>
<tr>
<td>2010</td>
<td>3rd decade: Multilayer HTS SQUIDs</td>
</tr>
<tr>
<td>2015</td>
<td>SQUID systems for field use</td>
</tr>
<tr>
<td>2020</td>
<td>SUSTERA</td>
</tr>
</tbody>
</table>

Outline

(1) 1st decade: GB JJ
(2) 2nd decade: Ramp-edge JJ, HTS SFQ devices
(3) 3rd decade: Multilayer HTS SQUIDs
(4) Application of multilayer HTS SQUIDs (field use)
(1) 1st decade: GB JJ

Superconducting Sensor Laboratory
(founded by Japan Key Technology Center, Hitachi, SEI, Yokogawa, SII, Shimadzu, ...)

LTS SQUIDs 64 ch MCG system (Hitachi) in 2nd decade
HTS SQUIDs using step-edge junctions
demonstration of 16 ch MCG

SQUITEM 1,2 (JOGMEC, SEI)
Metallic contaminant detection (TIT)
51 ch MCG system (Hitachi, Bicrystal JJ)

ISTEC
Materials research
GB junctions using FIB technique
weak-link, a/c GB junction

Hg-1212 bicrystal JJ and SQUIDs

(1) 1st decade: GB JJ


(2) 2nd decade: Ramp-edge JJ

- Developments of HTS multilayer structures with ramp-edge JJs for HTS SFQ devices (supported by New Energy and Industrial Technology Development Organization)

  NEDO project “Fundamental technologies for superconductivity applications” (FY98-03)
  ISTEC, Hitachi, Toshiba, Fujitsu, NEC, Sanyo, DuPont, AIST

  NEDO project “Superconductor Network Device” (FY03-06)
  ISTEC, Hitachi, Fujitsu, Advantest

- Interface-engineered junction (IEJ)


Small $I_c$ spread preferable to SFQ circuits
(2) 2nd decade: Ramp-edge JJ

IEJ: Formation mechanism

(2) 2nd decade: Ramp-edge JJ

IEJ: Formation mechanism

High $T_s$, $J_c: >10^5$ A/cm$^2$

Interface composition after YBCO deposition depends on $T_s$, $t_{dep}$

Low $T_s$, $J_c:10^4$-$10^5$ A/cm$^2$

Mutual atomic diffusion at the interface has a significant role
Precise control of deposition conditions required, but actually possible

(2) 2\textsuperscript{nd} decade: Ramp-edge JJ

\textbf{IEJ: Properties}

(a)  
\begin{align*}
X & : 1.0 \text{ mV/div.} \\
Y & : 0.2 \text{ mA/div.}
\end{align*}

(b)  
\begin{align*}
X & : 1.0 \text{ mV/div.} \\
Y & : 0.2 \text{ mA/div.}
\end{align*}

$I$-$V$ characteristics at 4.2 K

$I_c R_n$ product = 1.5-2 mV

\[1\sigma I_c \text{ spread} = 7.3\%\]

$X: 0.5 \text{ V/div.}$  
$Y: 1 \text{ mA/div.}$

$I$-$V$ characteristics for 1000-JJ array at 4.2 K

\begin{center}
\textbf{IEEE CSC \& ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.}

Distinguished presentation 2-FA-D-1 given at ISEC, 28 July-1 August 2019, Riverside, USA.
\end{center}
(2) 2\textsuperscript{nd} decade: Ramp-edge JJ

Multilayer structure

- 3 La-substituted RE-123 layers with SrSnO\(_3\) (SSO) insulator
  - \(R_\sigma\) of SSO/HTS/SSO/HTS sputtered multilayer < 2 nm
- Ramp-edge-type JJs (modified barrier) with 1\(\sigma\) \(I_c\) spread 5-10 %
- Minimum junction width of 1.5 \(\mu\)m
- Oxygenation of GP through via holes (550 \(\text{\degree C}\), 10 h, slow cool down)
- GP patterning, LT-SSO insulator, Au CPW lines for sampler
- V-Ti resistor with sheet resistance of 5-25 \(\Omega\).

Distinguished presentation 2-FA-D-1 given at ISEC, 28 July-1 August 2019, Riverside, USA.
(2) 2nd decade: HTS SFQ devices

HTS SFQ 1:2 de-multiplexer (50 JJs integrated)


HTS Sampler circuit with a potential bandwidth over 100 GHz (15 JJs integrated)
(2) 2nd decade: HTS SFQ devices

Demonstration of desk-top sampler system at ISTEC (40 K operation)

(H. Suzuki et al., ISEC2007, Washington DC)

HTS Sampler circuit with a potential bandwidth over 100 GHz (15 JJs integrated)
Why multilayer HTS SQUIDs?

- All commercial HTS SQUIDs consist of single HTS layer and GB JJs.
- By multilayer structure such as in LTS SQUIDs, higher performance is expected.

Without high-angle GB, higher tolerance against application of magnetic field expected
Lower probability of flux trapping

More complicated devices such as multichannel SQUID array can be easily fabricated using cross-over structure and ramp-edge JJs.
Cross-section of multilayer HTS SQUIDs

- SmBCO and La-ErBCO \( (T_c > 90 \text{ K}) \) electrodes
- Deposition of thin Cu-deficient layer on ramp surface before upper HTS deposition
  - Stable operation at 77 K
- Lower black-color insulating layer (Ga-PrBCO)
  - Higher uniformity of JJ properties on chip
Standard directly-coupled magnetometer

@ 77 K

Magnetometer (Module)

Field Noise [ fT/Hz^{1/2}]

Frequency [ Hz ]

~30 fT/Hz^{1/2}

dc bias

ac bias

+ mostly used for TEM systems for exploration of metal, geothermal, oil resources
Magnetometer with integrated input coil

- Josephson junction
- Base electrode (Washer)
- Counter electrode
- Pickup loop
- Input coil
- Superconducting contact

13.5 mm
2.2 mm

Magnetometer with integrated input coil

**Gradiometers**

- 5-ch gradiometer array: 1mm
- 10-ch gradiometer array: 0.5 mm

**Two-axis gradiometer**

Gradiometer for use with external pickup coil

Gradiometer module

- enable flexible system design
- mostly used for NDT systems
- magnetic immunoassay system

(4) Application of Multilayer HTS SQUIDs

- Non-destructive testing (NDT)
  multi-filamentary coated conductor, infrastructure (expressway bridge)

- Exploration/Monitoring of natural resources (ground TEM)
  metal deposit, geothermal reservoir, oil reservoir

- Monitoring of CO₂ EOR (borehole TEM), CCS

- Liquid-phase assay using magnetic nanoparticles, ULF-NMR/MRI


Highly-sensitive magnetic nondestructive testing
for deterioration diagnosis and maintenance of infrastructure

R&D Leader: Prof. Keiji Tsukada (Okayama University)
K. Tanabe (SUSTERA)
T. Furukawa (JAPEIC)
T. Sasayama (Kyushu Univ.)

compact NDT system with MR sensor
highly-sensitive NDT system using SQUIDs
simulation, pulse ECT method with MR sensor
inverse problem

“Technology for maintenance, renewal, management of infrastructure” program
Cross-ministerial SIP (Strategic Innovation Promotion Program) FY2014-2018
operated by Council for Science, Technology and Innovation, Cabinet Office

700,000 bridges, 100,000 tunnels many of them older than 50 years
huge maintenance cost has to be saved by technologies
Highly-sensitive magnetic nondestructive testing for deterioration diagnosis and maintenance of infrastructure

Target of NDT system with HTS-SQUIDs: Fatigue crack in steel deck plate

- We have developed an HTS-SQUID eddy current testing (ECT) system to detect fatigue cracks through asphalt pavement.
- SQUID has high sensitivity even at low frequencies
detection at larger lift-off
detection of non-through crack \((\delta = (2/\mu \sigma \omega)^{1/2})\)expected

[1]: A. Tabata et al., “Inspection and reinforcement for fatigue damages on orthotropic steel deck bridge”, Hanshin Expressway Company Limited, Japan
Highly-sensitive magnetic nondestructive testing for deterioration diagnosis and maintenance of infrastructure


Detection of 50 mm slit at 100 mm lift-off possible

Re signal
Non-through slit
Length = 50 mm
Depth = 2 mm

Im signal
Red: positive
Blue: negative
Highly-sensitive magnetic nondestructive testing for deterioration diagnosis and maintenance of infrastructure

Prototype road inspection system

Field test on expressway bridge (Oct. 2018)

Example of inspection results

No through crack
SQUITEM-III
for exploration of metallic deposit

Transient electromagnetic (TEM) method

Normalized field

Time (s)

10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0

Normalized secondary field

Late time data from deeper underground

TEM system using multilayer HTS SQUID

SQUID Magnetometer (by ISTEC)

Receiver (by MINDECO)

15 kg

10.6 kg

2.5 kg

60 cm

# Compact design
# Vacuum maintenance free
# Keep LN2 for 17 h
# > x 10 higher slew rate (10.5 mT/s)
  (> x 20 higher S/N)

Development of improved SQUITEM-III (FY2015-FY2016) x, y, z 3-component SQUID sensors tested in Australia field

SUSTERA has two SQUITEM-III systems for new application

Actual exploration in Peru

Field test result in Australia

Sedimentary rock layer including graphite

46.0m
10
2.15
0.46
0.1

200m
Fe content (ICP-AES analysis)

Cu content (ICP-AES analysis)

Sea level
0m
-200m
-400m
-600m

Distinguished presentation 2-FA-D-1 given at ISEC, 28 July-1 August 2019, Riverside, USA.
Exploration of geothermal reservoir

LOTEM (Long-offset TEM) using SQUITEM

Boundary found by Gravity survey

NEDO results briefing meeting
Exploration of geothermal reservoir

Boundary found by Gravity survey

Higher spatial resolution
Lower exploration cost

C: conductive zones
R: resistive zones

NEDO results briefing meeting
Monitoring of oil reservoir

Field test using SQUITEM was performed in November 2017. Collaboration between PTTEP and JOGMEC (MINDECO and SUSTERA joined.)

Transmitter Site
Arrangement of the transmitter
Signals for operating the generator
confirmation of transmission waveform

Receiver Site
Sugarcane
Rice field
Moving the receiver

Sirikit oil field (Thailand)
Oil reservoir at -2000 m EOR by water flooding

V. Hansamuit (PTTEP) @JOGMEC Techno Forum 2018
Monitoring of oil reservoir

Field test using SQUITEM was performed in November 2017. Collaboration between PTTEP and JOGMEC (MINDECO and SUSTERA joined.)

- Promising Outcome
- 2nd Survey is planned
- Extend to 3D model

Resistivity Map of SQUITEM 1D inversion

V. Hansamuit (PTTEP) @JOGMEC Techno Forum 2018
Monitoring of CO₂ EOR (Borehole TEM)

Schematic of enhanced oil recovery (EOR) technology utilizing CO₂ injection

- Insufficient sensitivity of conventional induction coil sensor → short distance
- Owing to high sensitivity of SQUID even at low frequencies
EM in wells with steel casing and the distance > 1000 m expected

Technical challenges:

- HTS-SQUID receiver (magnetometer) usable in high pressure (30-70 MPa) and high temperature (200 °C) environment
Monitoring of CO$_2$ EOR (Borehole TEM)

Development of elemental technologies

FY2012  JOGMEC “Innovative technology in oil and gas development field” program
FY2013-2015  JOGMEC “Technical solution project”

SQUID receiver system for use in a test well

JOGMEC Kashiwazaki test field

Stable operation in borehole filled with oily water at $\sim$300 m confirmed.

Test results indicated a possibility of long distance EM logging $>1000$m.

Monitoring of CCS (CO₂ capture and storage)


Possibility of applying TEM (LOTEM) to monitoring

Difference of transient curves (numerical simulation) (with and without CO₂)  100A transmitter current

Image of TEM observation
New development of cooling technique

Cooling with liq. N₂ in a glass Dewar

+ Heat inflow determines holding time of LN₂.
+ Heat inflow due to thermal conduction through glass wall and radiation from thermal insulator is dominant.

Hybrid cooling system
+ enables long-time operation in the sea

Issues:
+ How to remove cooler heat
+ good thermal contact
+ vibration & noise

Initial results will be presented by T. Hato at EUCAS2019
Summary

HTS multilayer and ramp-edge junction technologies developed for HTS SFQ circuits were successfully applied to the development of multilayer HTS SQUIDs with relatively high tolerance against application of magnetic field.

Using such multilayer HTS SQUIDs, a variety of systems for use on the ground or road, and in a borehole have been developed and demonstrated.

At SUSTERA, we will try to further expand HTS-SQUID application, for example, from subsurface to subsea in the near future.
Collaborators

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