Superconducting Tunnel Junction Detectors for Mass Spectrometry

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Abstract

   With conventional mass spectrometry (MS), ions are separated according to mass/charge (m/z) ratios. We must speculate the z values to obtain the m values. Superconducting tunnel junction (STJ) detectors can solve this problem, and true mass spectrometry becomes possible instead of m/z spectrometry. The STJ detectors were installed in MS instruments with a variety of ion sources. As an example, we report fragmentation analysis of a non-covalent protein complex of hemoglobin.

Keywords : superconducting tunnel junctions, Mass spectrometry, analytical instruments, protein complex, hemoglobin

I. Introduction

   Superconducting tunnel junctions (STJs) are classified into quantum detectors that directly convert incoming quanta into electric signal in contrast to calorimeters that measure temperature rise [1]. The amplitude of an electric output pulse is roughly proportional to the energy of a quantum divided by the superconducting energy gap (2Δ) of an electrode that absorbs the quantum. Observable electric signal is the tunneling current increase due to Cooper-pair breaking upon such events as photon absorption or ion impact, when the junction is biased within a subgap region normally less than Δ [2].

   Because of the existence of the energy gap, the performance of STJs is insensitive to temperature variation as long as they are kept less than about 0.5 K that depends on superconductor materials and electrode layer structures. This is an advantage over calorimeters that are sensitive to base temperature drift.

The insensitivity to temperature variation is essential for low energy ion detection, because we cannot avoid incoming black body radiation through an open hole that is necessary for ion impact on the detector surface. The heat input results in a base temperature rise. In addition, the temperature insensitivity ensures a long steady operation without peak shift. The stability is an important issue for analytical instruments.

   Mass spectrometry (MS) is defined as a method to measure the mass/charge (m/z) ratios of ions. After molecules are ionized, the ions are accelerated by a static acceleration voltage (V) of 3 – 30 kV and acquire the kinetic energy of $\underline{zV}$ eV. The ions with the same m/z value equally respond to electromagnetic fields. Therefore, one of the fundamental limits of MS is that z values are speculative, so that MS cannot determine m values uniquely.

   One of the popular ion separation methods is time of flight (TOF) between the ion acceleration and detection at a certain flight length (l). The TOF value is expressed by

$$\text{TOF} = \sqrt{m/2zeV}\ l. \tag{1}$$

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The *m/z* values for individual ions can be calculated from the TOF values. Conventional ion detectors count ions or measure ion flux. On the other hand, STJs can measure the *zV* values of ions, although it is the energy deposited to the detector surface strictly. Therefore, it is possible to determine the *z* values. The first application of STJ detectors to MS was reported by D. Twelenbold [3]. A review paper summarized the works before 1999 [4]. In this paper, we report the recent progress on instrumentation with STJ array detectors and an example of the practical analyses.

II. Experiments

The STJ array detectors with 100 pixels with an active area of 4 mm^2 were fabricated in AIST microfabrication facilities. The STJ detectors for MS are in principle the same as those for soft X-ray absorption spectroscopy [5, 6]. In 2005, the largest array detector had 16 pixels with an active area of only 0.64 mm^2 [7]. Figure 1 shows the photograph of an latest STJ array detector with 100 pixels. The detector is set at the end of the 0.3 K cold finger shown in Fig. 1 (b) [8] which is connected to the ^{3}He pot.

Recently, we built new clean room for analog-digital superconductivity (CRAVITY) [9] for the improvement of junction quality and array size. In addition, a multi-stop time-to-digital converter with single flux quantum (SFQ) circuits will be fabricated.

One of the difficulties in the MS application is the open space between the STJ detectors at 0.3 K and the ion source at room temperature as described above. In order to reduce the black body radiation from room temperature, a filter that reflects infrared rays but transmits ions was installed in front of the detector on the second pulse tube stage of 3 K together with a honeycomb collimator. The filter reduced the radiation heat input from 3 mW to 30 µW [10], which ensures the stable STJ operation. The bonding wires were connected to 45 cm-long Cu coaxial cables between the detector and the ^{3}He pot to avoid cross talk. The Cu coaxial cables were then connected to NbTi coaxial cables placed between 0.3 K and 3 K to keep a high
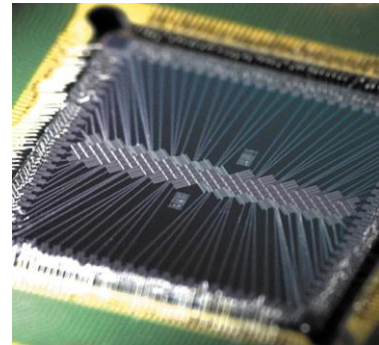
(a)
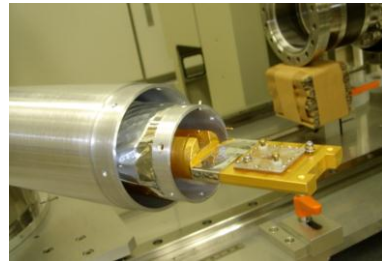
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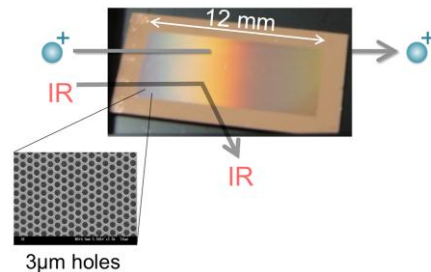
(c)

Fig. 1. STJ array detector with 100 pixels for ions at 0.3 K (a), cold finger for mounting detector (b), and infrared filter at 3 K to block room temperature radiation (c). The 200 µm-square pixels are arranged horizontally to fit to ion beam shape. The wiring leads connect the pixels and the bonding pads on the periphery of the 1 cm-square chip. The ions transmit the IR filter through the numerous holes with a few µm diameter.

band width of 7 GHz [11]. The heat input of the 100 NbTi coaxial cables with a length of 40 cm was only about 3 µW. Thus, the total heat input to the ^{3}He pot was 33 µW that is considerably less than a cooling power of 100 µW at 0.3 K. No liquid He supply is

needed. The holding time of the ³He cryostat was 44 h.

The current pulses for individual ions were converted to voltage pulses by preamplifiers at room temperature. The voltage pulses were digitized by 100 channel ADCs. Each TOF value for a single ion, which is a time lag between a trigger of pulse acceleration (or ionization laser shot) and an output pulse was obtained by digital signal processing with field-programmable gate array (FPGA) shown in Fig. 2. At the same time, the pulse height for each ion was also recorded to measure the deposited energy of the ion. The detail of the data processing system will be reported elsewhere.
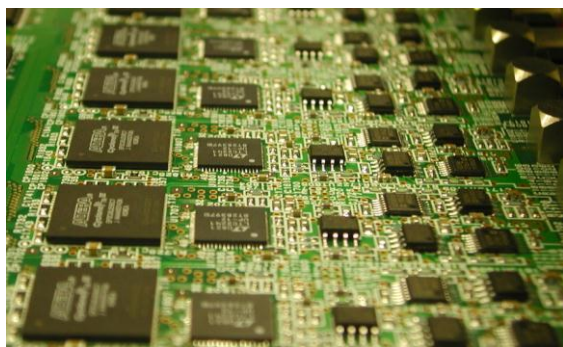

Fig. 2. 100-channle FPGA-based DSP circuits. Time-of-flight (TOF) values and kinetic energy values deposited to the STJs for individual ions (or neutral fragments) are recorded.

III. Experimental results

An example of the data measured by the ESI TOF MS with the STJ detector is shown in Fig. 4. The sample was hemoglobin that is a non-covalent protein complex of two α units, two β units, and four heme groups. The ESI produces multiply charged ions and there is a charge state distribution. Figure 4 (b) shows conventional mass spectra (*m/z* vs. ion count). Peak assignment is difficult because of unknown *z* values .

Fig. 3. ESI TOF MS equipped with STJ array detector with 100 pixels. The detector is cooled by the cryogen-free 0.3 K cryostat on the left hand side.

The weak non-covalent bonds in hemoglobin are easily broken during ionization or at the air-vacuum interface. The hemoglobin molecules were measured at two different voltages of the air-vacuum interface orifice. At a low orifice voltage, intact hemoglobin monomers to hexamers without dissociation were identified as ions with +7 to +23. On the other hand, as shown in Fig. 4, at a high orifice voltage, the hemoglobin complex dissociated into the α, β, and hemo units. The charge state ambiguity can be avoided by using the STJ data. Figure 4 (a) shows the kinetic energy vs. *m/z* scatter plots for individual ions. The event groups were identified as mainly monomers of

the α or β units with charge numbers of +3 to +9 and the singly-charged heme group.
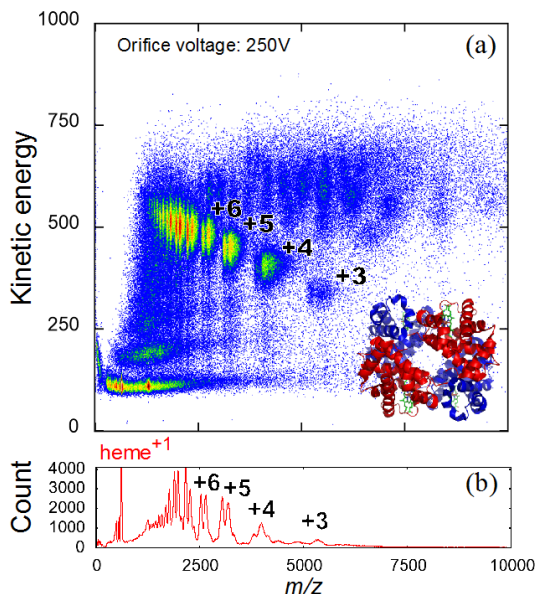

Fig. 4. Kinetic energy (charge number) vs. *m/z* scatter plot (a) and conventional mass spectrum reconstructed from the scatter plot data (b).

IV. Conclusions

The kinetic energy measurement with the STJ detectors is useful to determine the charge numbers of ions and then the *m* values uniquely. In hemoglobin, it has been confirmed that the heme molecules are always singly-charged, while the α and β units are multiply-charged from +3 to +9.

The kinetic energy measurement was also used to separate N^+ and N_2^{++}, both of which have exactly the same *m/z* of 14 [12]. Furthermore, direct analysis of neutral fragments was realized, and another MS problem of neutral loss was solved [13].

Acknowledgments

References

[1] M. Ohkubo, "Current status of non-equilibrium superconducting detectors for photons and molecules", AIP Conf. Proc. 1185, 381-388 (2009).

[2] M. Ohkubo, "Superconducting detectors for particles from atoms to proteins", Physica C, 468, 1987-1991 (2008).

[3] D. Twerenbold *et al.*, "Detection of single macromolecules using a cryogenic particle detector coupled to a biopolymer mass spectrometer, Appl. Phys. Lett. 68, 3503-3505, (1996).

[4] M. Frank, S. Labov, G. Westmacott, and W. Benner, "Energy-sensitive cryogenic detectors for high-mass biomolecule mass spectrometry", Mass Spec. Rev. 18, 155-186 (1999).

[5] M. Ukibe *et al.*, "Soft x-ray detection performance of superconducting tunnel junction arrays with asymmetric tunnel junction layer structure", Jpn. J. Appl. Phys. 51, 010115-1-010115-5 (2012).

[6] M. Ohkubo *et al.*, "X-ray absorption near edge spectroscopy with a superconducting detector for nitrogen dopants in SiC", Sci. Rep. 2, 831-1-831-5 (2012).

[7] R. Wenzel, U. Matter, L. Schultheis, and R. Zenobi, "Analysis of Megadalton Ions Using Cryodetection MALDI Time-of-Flight Mass Spectrometry", Anal. Chem. 77, 4329-4337 (2005).

[8] http://www.vacf.jp/systems_e.html.

[9] http://unit.aist.go.jp/riif/openi/index.htmlS. Shiki *et al.*, "Infrared-blocking filters for superconducting-tunnel-junction particle detector", Jpn. J. Appl. Phys. 47, 3682-3685 (2008).

[10] A. Kushino *et al.*, "Development of superconducting coaxial cables for cryogenic detectors", J. Low Temp. Phys. 151, 650-654 (2008).

[11] N. Zen *et al.*, "Cryogen-free cryostat for low temperature hundred pixel array detectors", IEEE Trans. Appl. Supercond. 19, 1008-1011 (2009).

[12] S. Shiki *et al.*, "Kinetic-energy-sensitive mass

spectrometry for separation of different ions with the same *m/z* value", J. Mass Spectrom. 43, 1686-1691 (2008).

[13] M. Ohkubo *et al*., "Direct mass analysis of neutral molecules by superconductivity", Int. J. Mass Spectrom. 299, 94-101 (2011).