ISSN 0020-4412, Instruments and Experimental Techniques, 2006, Vol. 49, No. 6, pp. 868–871. © Pleiades Publishing, Inc., 2006.
Original Russian Text © M.G. Kozin, I.L. Romashkina, S.A. Sergeev, L.V. Nefedov, V.P. Koshelets, L.V. Filippenko, 2006, published in Pribory i Tekhnika Eksperimenta, 2006, No. 6, pp. 135–139.

LABORATORY TECHNIQUES

A Pulse-Height Spectrum from a Mössbauer ^{57}Co Source Registered with a Superconducting Tunnel Detector

M. G. Kozin[a], I. L. Romashkina[a], S. A. Sergeev[a], L. V. Nefedov[a], V. P. Koshelets[b], and L. V. Filippenko[b]

[a] Skobeltsyn Institute of Nuclear Physics, Moscow State University, Vorob'evy gory 1, str. 2, Moscow, 119992 Russia
[b] Institute of Radio Engineering and Electronics, Russian Academy of Sciences, ul. Mokhovaya 11, corp. 7, Moscow, 125009 Russia

Received January 18, 2006; in final form, March 24, 2006

Abstract—Pulse-height spectra from irradiation of superconducting tunnel detectors of an original design with quanta emitted by a Mössbauer ^{57}Co source were recorded in the energy range 1–15 keV. The detectors have a layer structure of Ti/Nb/Al,AlO_x/Al/Nb/NbN (with thicknesses of 30, 100, 8, 13, 150, and 30 nm, respectively), one active electrode, and one passive electrode (the signal of which is suppressed owing to the presence of a titanium sublayer). Thanks to the high activity of the source, a 14.4-keV γ line has been detected. The spectra obtained with ^{57}Co and ^{55}Fe sources are compared. The energy dependence of the detector response is determined using the positions of the fluorescence lines from construction materials and specially selected shields. The Mg, Al, SiK_α, and Ag, InL_α lines, along with the Mn$K_{\alpha,\beta}$, Fe$K_{\alpha,\beta}$, 14.4-keV γ lines and niobium escape lines, were used for this purpose. The possible reasons for a strong nonlinearity of this dependence are pointed out.

PACS numbers: 29.40.Wk, 85.25.Oj, 74.50.+r, 74.45.+c

DOI: 10.1134/S0020441206060182

INTRODUCTION

Superconducting tunnel junctions (STJs) are promising for detection of X rays and soft γ rays because they are characterized by a higher energy resolution than the best semiconductor detectors and are being currently used for X-ray fluorescence analysis, in astronomy, and other applications [1].

However, the energy resolution achieved at present is lower than the theoretical value calculated with consideration of the contributions that lead to additional line broadening. Therefore, studying the physical processes that occur in STJs during absorption of radiation quanta at different energies and affect the performance parameters of detectors is a pressing task from the standpoint of more active use of these detectors in a wide spectral range.

The number of quasi-particles yielding a tunnel-current pulse registered by a detector is proportional to the energy of incident quanta [2], and, in the first approximation, the detector response must be a linear function of energy. However, this proportionality is valid only for a bulk homogeneous superconductor and may be violated in a multilayer structure [3] that possesses the proximity effect. In addition, the rate of loss of the already produced quasi-particles may depend on their initial number. Both of these factors may lead to a nonlinear response of the detector as a function of energy.

Such detectors are usually tested with a ^{55}Fe radioactive source emitting MnK_α and MnK_β X-ray lines with energies of 5.893 and 6.490 keV, respectively. The detector's nonlinearity can be revealed even with this source from a mismatch between the distances between the above lines and the spectrometer's readings according to calibration by any of them. However, practical use of the detector requires that its energy be calibrated more precisely.

The detector's responses in a wider energy range (1–10 keV) are commonly studied using either characteristic X rays excited by an electron beam [4], a collimated synchrotron beam [5], or synchrotron-radiation-excited X-ray fluorescence [6].

Earlier, along with a conventional ^{55}Fe radioactive source, we already used a Mössbauer ^{57}Co source, as well as Ti and Ca X-ray fluorescence excited by the latter [7], to study the detector's response linearity at energy of up to 7 keV. In this study, the detector's response has been studied with a more intense source in a wider energy range (1–15 keV).

EXPERIMENTAL TECHNIQUE

STJs with the structure of Ti/Nb/Al,AlO_x/Al/Nb/NbN (with thicknesses of 30,100,8,13,150, and 30 nm, respectively) were manufactured by the method of magnetron sputtering on a Si substrate with a buffer layer of amorphous Al_2O_3. The upper Al/Nb/NbN electrode is active; Nb contained in it is the main absorber, while the NbN layer serves as the reflector of quasi-particles from the outer surface, and the Al layer is a trap

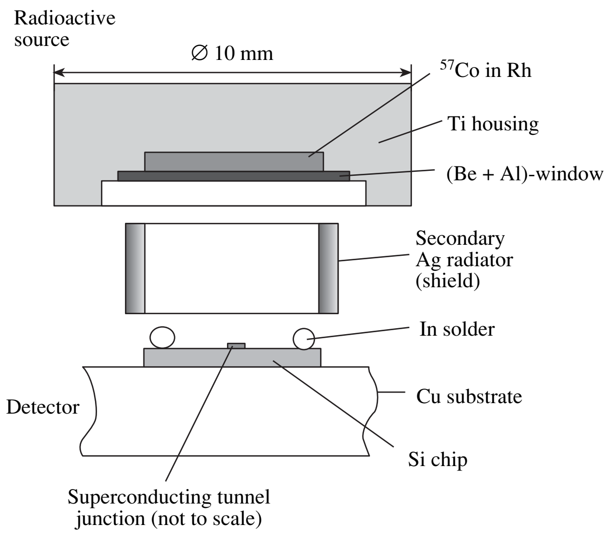

Fig. 1. Geometry of the experiments on fluorescence excitation and detection.

that increases the tunneling probability. The lower Ti/Nb/Al electrode is passive, and the signals from it are attenuated considerably owing to the efficient collection of quasi-particles in the Ti-layer trap located on the opposite-to-the-barrier side of the electrode. The electrodes of the STJ have the shapes of rhombs with a diagonal length ratio of 1 : 4 and an area of 20000 μm^2. More detailed characteristics of this type of junctions with different areas (the current–voltage characteristics and differential resistances of junctions, pulse-height spectra arising during irradiation with X rays from the ^{55}Fe source, characteristic lifetimes, and tunneling and carrier-loss times) are presented in [8, 9].

The pulse-height spectra arising during irradiation of STJs with X-ray photons from radioactive sources and secondary radiators were recorded at temperatures T = 1.3–1.4 K in a magnetic field H ~ 100 Oe applied in parallel to the plane of the tunneling barrier to suppress a Josephson current.

A charge sensitive preamplifier operated at room temperature.

The detector, the ^{57}Co in an Rh host source with an activity of ~20 mCi, and secondary radiators were placed in a vacuum chamber immersed in an evacuated helium cryostat (Fig. 1). A ^{55}Fe source with an activity of <1 mCi was also used; in this case, a ~26-μm-thick magnesium foil was inserted between the source and detector.

EXPERIMENTAL RESULTS

The pulse-height spectrum measured at T = 1.325 K, H = 138 Oe, and detector bias voltage V = 0.935 mV with a tunnel detector irradiated for 8130 s with radiation from the ^{57}Co radioactive source in the presence of a second Ag radiator is shown in Fig. 2a. The drifts of the position of the line of the precise-amplitude generator, bias voltage, and temperature were 0.24%, 0.010 mV, and 0.001 K, respectively.

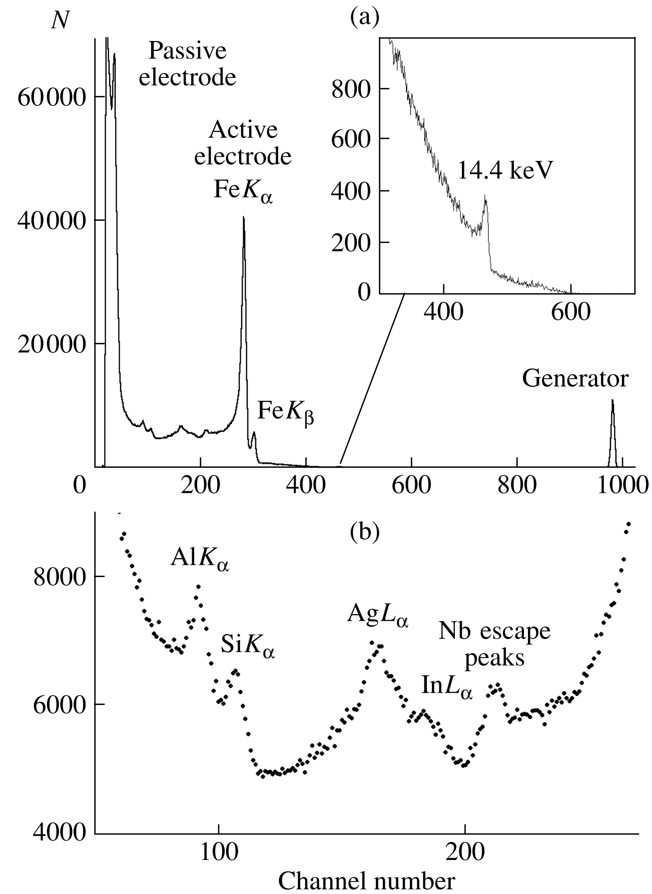

Fig. 2. Pulse-height spectrum arising during irradiation of a detector with radiation photons from a Mössbauer ^{57}Co source. Different portions of the spectrum are represented at different scales.

Apart from the signal from the precise-amplitude generator, the FeK_α (6.400 keV) and FeK_β (7.057 keV) narrow lines are observed in this spectrum; they correspond to the radiation absorption in the active electrode. The signal from the passive electrode is attenuated considerably as compared to the signal from the active electrode; the former is located in the region of low energies and is observed against the background associated with the detector response to phonons produced in substrate during absorption. Less intense lines can be seen between the lines responsible for the absorption in the active and passive electrodes. Figure 2b shows this spectral region with the following lines on a magnified scale: the AlK_α fluorescence line (1.487 keV) from a 10-μm-thick Al film coating the source's beryllium window, the SiK_α line (1.740 keV) from the silicon substrate, the AgL_α line (2.984 keV) from a ring Ag shield, and the InL_α line (3.287 keV) from small indium contacts (at the place where copper electric leads are connected to the chip). A complex observed at higher energies (4.17–4.23 keV) is related

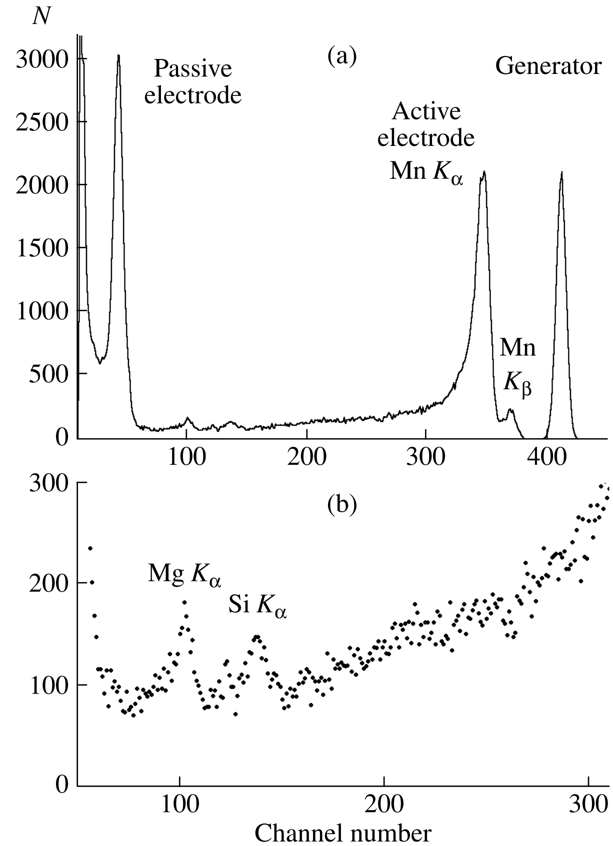

Fig. 3. Pulse-height spectrum arising during irradiation of a detector with photons from a ^{55}Fe source. Different portions of the spectrum are represented at different scales.

to the lines of radiation escape from the film and caused mainly by the L_{II}–M_{IV} and L_{III}–M_V electron transitions in niobium with energies of 2.26 and 2.17 keV, respectively.

In the region of energies exceeding the energy of the FeK_β line, a "tail" and peak from the absorption of γ quanta with an energy of 14.4 keV are observed. This spectral region is presented on a magnified scale in the inset of Fig. 2a. At higher energies (channels 480–700), the tail's slope decreases noticeably.

To demonstrate clearly the differences between the detector responses to excitations with high- and low-energy photons, Fig. 3a shows a pulse-height spectrum arising under irradiation of the same detector for 3276 s with radiation from the ^{55}Fe radioactive source, in the spectrum of which radiation with an energy higher than 6.49 keV is absent. This spectrum has been measured at $T = 1.329$ K, $H = 138$ Oe, and detector bias $V = 0.356$ mV and is represented as the sum of four separate spectra recorded independently to control their stability. The spectrum contains the MnK_α and MnK_β lines corresponding to complete absorption of radiation in the active electrode; a signal from the passive electrode and a rise in the region of low energies are also observed. The weak MgK_α and the SiK_α lines, which are also shown in Fig. 3b on a magnified scale, can be seen between the lines responsible for the absorption in the active and passive electrodes. Statistics does not allow identification of the fluorescence lines of the indium contacts and Nb escape lines in this spectrum.

DISCUSSION

The comparison of the radiation spectra from different radioactive sources obtained with a common detector (Figs. 2 and 3) shows that, in Fig. 3, the signal from the passive electrode is recorded more sharply, and the rise in the low-energy spectral region is shifted toward lower energies. This difference is evidently explained primarily by different absorptions of radiations at energies of ~6 and 14.4 keV or higher in the substrate material and also by slightly differing phonon transfer of the arising excitation from Si to Nb.

The differences in the shape of the pedestal at the background of which the 6-keV (Figs. 2a and 3a) and 14.4 keV (inset in Fig. 2) lines are observed are qualitatively similar to the differences described in [10] for the absorption of the MnK_α and AgK_α lines, which are caused by an escape of the photoelectron track from the detector's absorbing electrode and represented in the limits of thin and thick films.

A tail at high energies is caused by rare absorption events during detection of radiation at an energy >14.4 keV, as well as by a phonon signal from the absorption of this radiation in the Si substrate.

The absorption lines are asymmetric (see, e.g., FeK_α in Fig. 2a): they have abrupt right and broadened left edges (a low-energy "shoulder"). The main cause of inhomogeneous broadening is signal attenuation during diffusion of quasi-particles from the absorption region to the entire volume of the detector. The maximum response corresponds to absorption of a photon at the center of the detector, while, as the photon-absorption point moves to the periphery, the detector response diminishes.

To determine the line position and the full width at half-maximum (FWHM), we fitted the line to a Gaussian profile using the abrupt line's right edge and approximately half the left edge, where the effect of the inhomogeneous broadening is not too strong. The FWHM values obtained for the 6.4- and 14.4-keV lines (Fig. 2a) are 205 and 472 eV, respectively. With allowance for the contribution of electronic noises determined from the generator's peak width, the intrinsic linewidth was ~120 and 413 eV, respectively. The detector's intrinsic linewidth for the 6-keV line is in agreement with the data obtained in our studies [8, 9] with a similar detector but exceeds the best value obtained in [8, 9] for smaller detectors. The cause of a decline of the resolution with an increase in the dimensions of detectors has not yet been established.

A 150-nm-thick Nb film absorbs 3.5% quanta of the FeK_α radiation and 0.39% quanta of the 14.4-keV radi-

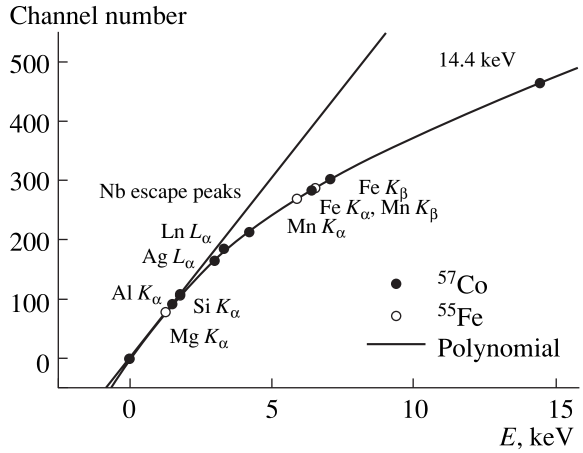

Fig. 4. Energy dependence of the detector's response.

ation. With allowance for a conversion coefficient of 9 in ^{57}Co, these values yield a ratio of the line intensities of 81 : 1, a value that has the same order of magnitude as the ratio for the spectrum shown in Fig. 2a. Note that the absorption of radiation at an energy of 14.4 keV in Ta is 3.7%, i.e., ten times higher than the absorption in Nb.

Figure 4 shows the energy dependence of the positions of the lines presented in Figs. 2 and 3. The data obtained in experiments with different sources were brought to the same scale via coincidence of the positions of the FeK_α (6.4 keV) and MnK_α (6.49 keV) lines with a linear account of the 1.4% difference of these energies (the positions of the SiK_α lines in different experiments). Beginning with an energy of ~2 keV, a noticeable deviation of the calibration from linearity is observed, which reaches a value of ~20% in the region of 6.4-keV energies. A straight line is drawn via fitting to points of zero, Mg, Al, and Si. The data obtained are insufficient for drawing a conclusion on whether this deviation begins at energies exceeding the *L* edge for Nb or occurs within the entire energy range 1–15 keV.

A typically observed nonlinearity is appreciably lower [4, 5]. These data have been obtained in [4, 5] on STJs with epitaxial layers. However, the calculated deviation reproducing a nonlinear response observed experimentally for polycrystalline Nb films reaches 12 and even 36% for films with ~150- and ~20-nm free paths of quasi-particles, respectively. It is suggested in [11] that the nonlinearity is related to intense self-recombination of quasi-particles in the region of their local excitation.

The physical causes of strong self-recombination leading to significant nonlinearity are objects of active theoretical and experimental studies. A significant increase in the time of phonon-induced breakdown of Cooper pairs, which is related to specific features of the density of states in structures with the proximity effect, such as the Nb/Al film, is considered in [3] as a cause of this nonlinearity. Another factor causing an intensified decay of excess quasi-particles may be related to the trapping of magnetic vortices in the detector's films [12].

Regardless of the nonlinearity-causing factors, the curve in Fig. 4 can be used as the calibration curve of the detector for determining the energy of unknown radiation. This curve is described by a fourth-power polynomial quite well.

CONCLUSIONS

Superconducting tunnel detectors with a Ti/Nb/Al,AlO_x/Al/Nb/NbN structure were used to record pulse-height spectra arising during irradiation of STJs with radiation quanta from a Mössbauer ^{57}Co source in the energy range 1–15 keV (a 14.4-keV γ line has been recorded). The shape of the spectrum obtained is compared to the spectrum from an ^{55}Fe source.

The AlK_α, MgK_α, SiK_α, AgL_α, and InL_α fluorescence lines from the construction materials and secondary radiators have been detected. These data allowed obtainment of the energy dependence of the detector's response in a wide spectral range using the additional data on the positions of the MnK_α, MnK_β, FeK_α, FeK_β, and 14.4-keV lines and the lines of radiation escape from niobium. This dependence is essentially nonlinear.

This detector can be used for high-resolution spectroscopy of soft X rays and γ rays in the presence of sources of sufficiently high intensity.

ACKNOWLEDGMENTS

The authors are grateful to V.S. Rusakov for his help in organizing the experiment.

REFERENCES

1. *Proc. of the XI Int. Workshop on Low Temp. Detectors (LTD-11)*, Tokyo, 2005, *Nucl. Instrum. Methods, Phys. Res.*, 2006, vol. A559, pp. 598, 728, 776, 779.
2. Rando, N., Peacock, A., van Dordrecht, A., et al., *Nucl. Instrum. Methods Phys. Res. A*, 1992, vol. 313, p. 173.
3. Kozorezov, A.G., *Nucl. Instrum. Methods Phys. Res. A,* 2000, vol. 444, p. 3.
4. Labov, S.E., Hiller, L.H., Mears, S.A., et al., *IEEE Trans. Appl. Supercond.*, 1995, vol. 5, p. 3034.
5. Verhoeve, P., Rando, N., Verveer, J., et al., *Phys. Rev. B*, 1996, vol. 53, no. 2, p. 809.
6. Labov, S.E., Frank, M., le Grand, J.B., et al., Abstracts of Papers, *Proc. VII Int. Workshop on Low Temp. Detectors (LTD-7)*, Munich, 1997, pp. 82–95.
7. Andrianov, V.A., Kozin, M.G., Romashkina, I.L., et al., Abstracts of Papers, *Proc. of the LV Nat. Conf. Nucl. Phys. "Frontiers in the Physics of Nucleus"*, St. Petrsburg, 2005, p. 329.
8. Kozin, M.G., Romashkina, I.L., Sergeev, S.A., et al., *Izv. Akad. Nauk, Ser. Fiz.*, 2005, vol. 69, no. 1, p. 36.
9. Kozin, M.G., Romashkina, I.L., Sergeev, S.A., et al., *Nucl. Instrum. Methods Phys. Res. A*, 2004, vol. 520, p. 250.
10. Van Vechten, D., Porter, F.S., Wood, K.S., et al., *IEEE Trans. Appl. Supercond.*, 1995, vol. 5, part 3, p. 3030.
11. Zehnder, A., *Phys. Rev. B*, 1995, vol. 52, no. 17, p. 12858.
12. Golubov, A.A., *Physica C*, 1993, vol. 205, p. 147.