SUPERCONDUCTING TRANSITION-EDGE SENSOR

FIELD OF THE INVENTION

This invention relates to particle detection, particularly x-ray detection, using an aluminum/normal-metal bilayer superconducting transition-edge sensor as a thermometer in a microcalorimeter.

BACKGROUND OF THE INVENTION

Detection of particles, including photons, molecules, electrons, ions and phonons, is essential to many industrial and research measurements. Although the present invention can be used for particle detection in general, it is particularly suited to x-ray detection, and the following discussion relates primarily to x-ray detection.

X-ray photon detectors usually directly detect other types of excitations that are generated by x-ray photons. In silicon and germanium based Energy Dispersive Spectroscopy (EDS) detectors, electron-hole pairs are generated by x-ray absorption events. Although EDS detectors are the most commonly used x-ray spectrometers for microanalysis, their energy resolution is limited to about 100 eV full width at half max (FWHM) by the counting statistics implied by the large size of the electron-hole pair excitation (a few electron volts (eV)). Superconductor/insulator/superconductor (SIS) tunnel junctions directly detect quasiparticles that are created by the incident x-rays and tunnel through the biased junction. As in semiconductor EDS detectors, the total current is indicative of the x-ray energy, but since the size of the quasiparticle excitation is much smaller (typically about a milli-electron volt (meV)), the theoretical energy resolution of SIS tunnel junction detectors implied by the carrier statistics is much better (a few eV FWHM.) Unfortunately, various effects tend to make the actual performance of SIS tunnel junctions significantly worse than the theoretical limit, and the best energy resolution that has been obtained with SIS tunnel junctions to date is 29 eV FWHM at 6 keV (Frank et al., Nucl. Inst. and Meth. A 370, 41 (1996)).

X-ray microcalorimeters instead convert the x-ray energy into heat in the form of hot-electrons or phonons, which can be a very efficient process. An x-ray microcalorimeter consists of an absorber to stop and thermalize incident x-rays and a thermometer to measure the resulting temperature rise. The first x-ray microcalorimeters used insulating or superconducting absorbers (for low heat capacity) and a semiconductor thermistor thermometer. While these achieve adequate energy resolution (7.1 eV FWHM at 6 keV), the response time is intrinsically slow. A recent microcalorimeter uses a normal-metal absorber and an NIS tunnel junction to measure the temperature rise (Nahum and Martinis, Appl. Phys. Lett. 66, 3203 (1991)). The response is fast but the energy resolution was limited to 18 eV FWHM at 6 keV by an unexpected noise source.

Superconducting transition-edge sensors have been proposed for use as a thermometer within an x-ray microcalorimeter (Irwin, Appl. Phys. Lett. 66, 1998 (1995), which is incorporated by reference herein in its entirety). The temperature of a superconducting film is held within the superconducting transition, and heat deposited in the film is measured via the strong temperature dependence of the film's electrical resistance in this region. For x-ray detection the optimum transition temperature is between about 50 and 150 mK. The choice of the T_c within this range depends on the desired detector parameters. Superconducting tungsten films having T_c=70 mK have been used for x-ray detection

(Irwin et al., IEEE Trans. Appl. Sup. 5, 2690 (1995)). For an elemental superconductor such as tungsten, the transition temperature tends to be a fixed property of the metal and is difficult to tune to suit specific applications. For alloys of superconductors with normal metals, the T_c can be adjusted but the transition edge is not sharp and the alloys are not stable.

The transition temperature can also be adjusted via the proximity effect in superconductor/normal-metal bilayers. When a clean interface is made between a superconducting film and a normal metal film, and the films are thinner than their coherence lengths, the bilayer acts as a single superconducting film with a transition temperature suppressed from that of the bare superconductor. By varying the relative film thicknesses, the T_c of the bilayer can be adjusted. Iridium/gold bilayers have been described for particle detection (Nagel et. al., J. Appl. Phys. 76, 4262 (1994)). The T_c of elemental iridium is 112 mK, which is within the target range for x-ray detection. In Ir/Au bilayers, Nagel et. al. report T_c's varying from 33 to 106 mK. However, the Ir/Au system is very difficult to reproducibly fabricate, it requires the substrate to be heated, it requires a very clean, high vacuum deposition system, and the transition temperature of such bilayers is limited to less than 112 mK. As shown in Table 1 and FIG. **3** of Nagel et al., the T_c cannot be reliably predicted as a function of the layer thicknesses, and a transition is not even observed in some instances.

It is desirable to develop a bilayer system that has a larger tunable transition range, that can be more easily deposited, that can be deposited without heating the substrate, that can be deposited in a deposition system with only moderate vacuum (~1e-7 torr), that is more reliably reproducible, and that has sharper superconducting transitions. The present inventors attempted to fabricate Ir/Au bilayer transition-edge sensors, but were unsuccessful. Titanium/normal-metal bilayers were fabricated, but the T_c was not reproducible, and the transition was broad. In searching for a suitable superconductor for use in a bilayer, aluminum was considered because of the ease of deposition of stable, low stress aluminum films with suitable hardness, low cost, and non-toxicity. It was, however, considered an unlikely candidate because the T_c for aluminum (1.1 K) would need to be suppressed by more than an order of magnitude to cover the target range for x-ray detection (50–150 mK), which seemed incompatible with sharp, reproducible transitions. In addition, the T_c of elemental aluminum is notoriously sensitive to contaminants and deposition conditions, making one think that the bilayer T_c would be unpredictable. It was therefore an unexpected and surprising discovery that aluminum/normal-metal bilayers have reproducible transition temperatures, that the T_c can be reduced by more than an order of magnitude, that the T_c is tunable in a predictable fashion as a function of the thicknesses of the individual layers, and that the transition edge is extremely sharp.

SUMMARY OF THE INVENTION

This invention provides a method and apparatus for particle detection utilizing an Al/normal-metal bilayer transition-edge sensor (TES) coupled with a particle absorber. The TES is maintained in the transition region where its properties are extremely sensitive to temperature. In the detector, the energy of an absorbed particle is converted to heat by the absorber and the transition from the bilayer's superconducting to normal state is used to sense the temperature rise. The transition temperature, T_c, of the bilayer can be reproducibly controlled as a function of the relative thicknesses and the total thickness of the supercon-