Dynamics of non-equilibrium quasiparticles in the superconducting cold-electron bolometer (SCEB)

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In this paper, the time evolution of the quasiparticle distribution in a small absorber of the superconducting cold-electron bolometer (SCEB) was modeled. The model used was based on the diffusion model developed for the superconducting tunnel junction with large absorbers. The result showed that the use of a small absorber led to faster response time of the bolometer. Compared to other types of infrared and microwave bolometer, the SCEB promises to perform better and faster and can easily be integrated with the read-out electronics.

KEYWORDS

Bolometer; Quasiparticle; Cosmic Microwave Background Radiation; Superconductors; Diffusion

INTRODUCTION

A bolometer is a device that measures electromagnetic radiation. Many types of bolometers have already been developed for different applications. One of the most interesting applications is the detection of millimeter and submillimeter waves. Such EM waves include infrared radiation and cosmic microwave background radiation (CMB). The CMB is radiation that emanated from the earliest times in the universe, around 400,000 years after the Big Bang.

The superconducting cold-electron bolometer (Kuzmin 2003, 2008) or SCEB is an ultrasensitive device for detection of infrared and microwave radiation. It consists of a superconducting absorber that is coupled to superconducting traps at its ends by a superconductor-insulator-superconductor (SIS) tunnel junction. The absorber is the most important component of the bolometer. Its design dictates the bolometer's sensitivity and temporal response to incident radiation. It is within the absorber that the photon is converted into quasiparticle energy. The tunnel junction facilitates the transfer of quasiparticles from the absorber to the quasiparticle traps. This transfer can be measured as a current through the junction. Thus, the current is an indirect measure of the number of photons that are absorbed. The purpose of the superconducting traps is to prevent quasiparticles from tunneling back into the absorber, which contributes to a negative current. The efficiency of the traps has already been studied (Agulo et al. 2004). It was found that the quasiparticle trapping is most efficient on a geometry of the superconducting electrodes that facilitates better quasiparticle diffusion, and with the addition of normal metal traps.

There are many types of bolometers using superconducting

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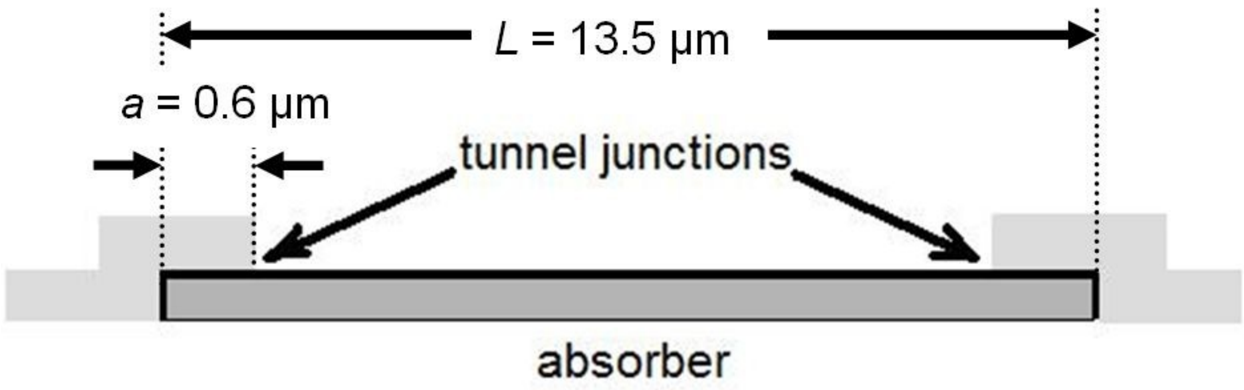

Figure 1. The superconducting cold-electron bolometer (SCEB). The SCEB is composed of a small volume absorber with length, *L*. At its two ends are tunnel junctions that serve as collectors of quasiparticles. The quasiparticles are generated when a photon is absorbed in the absorber.

absorbers. The article by Richards (1994) gives a comprehensive review of these. One of the most widely studied types is called the superconducting tunnel junction (STJ) detector. Such a detector uses a large volume of absorber. The principle of operation is quite different from that of the SCEB. The STJ detection is done by counting photons per unit energy, while the SCEB detects individual photons and converts them into current. The advantage of the former is energy resolution, while that of the latter is sensitivity.

The idea of this work is to study the dynamics of non-equilibrium quasiparticles that are absorbed by a small volume of superconducting material. The motivation is to understand what happens during absorption of photon energy in the absorber made of a small volume of superconductor. The model that will be described in the next section was developed by Ejrnaes et al. (2005) using a superconducting tunnel junction detector. It will be applied to the SCEB to determine the current-voltage characteristics and to estimate the bolometer response.

METHODOLOGY

The model developed by Ejrnaes et al. (2005) assumes that the absorption of photons generates quasiparticles with energies greater than the superconducting gap energy of the absorber. These quasiparticles then diffuse throughout the absorber, eventually ending up at the tunnel junctions. The role of the tunnel junction is to remove the quasiparticles from the absorber region. The magnitude of the resulting current carries information regarding the number of photons and the energy that each contributes.

One more assumption is peculiar to this model. While most STJs have large absorber areas, this model applies to long and narrow absorber strips as replacement for large absorbers. Such configuration, which have been named DROID (Distributed Read Out Imaging Device), makes it easier for STJs to be multiplexed. A single absorber corresponds to a single pixel. A microwave camera corresponds to millions of pixels. The method used to 'combine' the information from all of these pixels is called multiplexing. This configuration has also been demonstrated to have very good position and energy resolution (Li et al. 2001), which is essential for STJ bolometer operation.

The idea is to solve for the quasiparticle density, *n(x,t)* by solving a diffusion equation pertaining to the behavior of the quasiparticles. The diffusion equation is given by

$$\frac{\partial n(x,t)}{\partial t} = D\frac{\partial^2 n(x,t)}{\partial x^2} - \gamma(x)n(x,t),$$

$$\gamma(x) = \begin{cases} \gamma_1 = \gamma_{loss} + \gamma_{tunn} & Region\ 1\ \left(-\frac{L}{2} < x < -\frac{a}{2}\right) \\ \gamma_2 = \gamma_{loss} & Region\ 2\ \left(-\frac{a}{2} \le x \le \frac{a}{2}\right) \\ \gamma_3 = \gamma_{loss} + \gamma_{tunn} & Region\ 3\ \left(\frac{a}{2} < x < \frac{L}{2}\right) \end{cases}$$

where γ_{tunn} is the rate of quasiparticle tunneling through the junction, γ_{loss} is the loss rate, *D* is the diffusion constant, *L* is the absorber length and *a* is the width of the tunnel junction. The boundary conditions are the following: (1) there are no losses at the ends of the absorber; (2) the quasiparticle density is continuous at $x = \pm a/2$; (3) the spatial derivatives of the quasiparticle density are also continuous at $x = \pm a/2$. The initial condition is such that the point of impact of the photon on the absorber is anywhere within region 2. The mathematical details are described in detail by Ejrnaes et al. (2005). Their diffusion equation was also solved in this problem, using a different and simpler numerical method. The simulations to be presented do not include the effect of quasiparticle trapping (Pekola et al. 2000), which is a topic for further study.

RESULTS AND ANALYSIS

The SCEB design is very much similar to the long and narrow structure of the previously described DROID. The difference is that the SCEB absorber is much smaller in volume than that of the DROID. A small absorber volume means a small surface area in contact with the substrate, which would lead to lesser quasiparticle losses through the absorber. Ejrnaes et al. (2005) described their absorber to have a length of 775 µm. The SCEB has a typical length of 15 µm. As a consequence, the junction areas are considerably reduced as well. The DROID junction has a length of 50 µm, while the SCEB junction has a typical length of 1 µm.

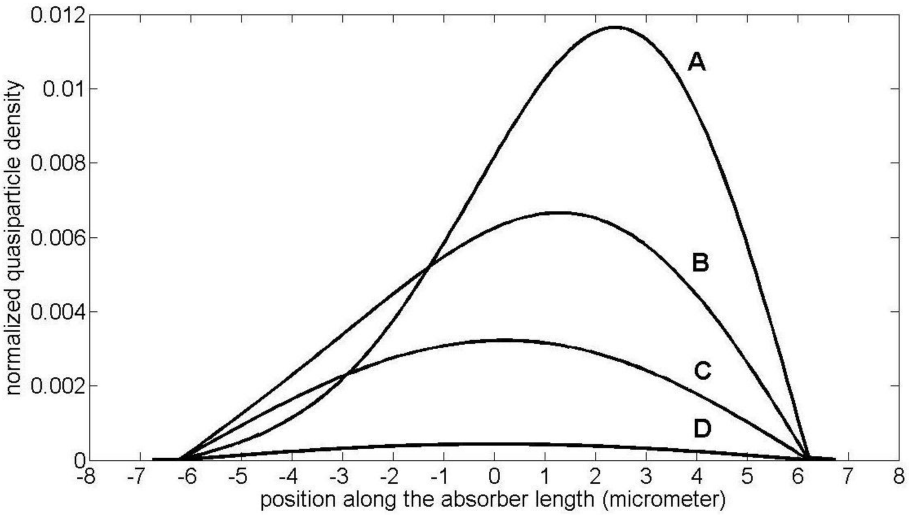

Figure 2: Quasiparticle density distribution over the whole SCEB absorber as a function of time. For the simulation, the total length of the absorber was 13.5 µm, while the length of a tunnel junction was 0.6 µm. The middle of the absorber corresponds to *x* = 0. The curves A, B, C, and D correspond to 50, 100, 200, and 500 time units.

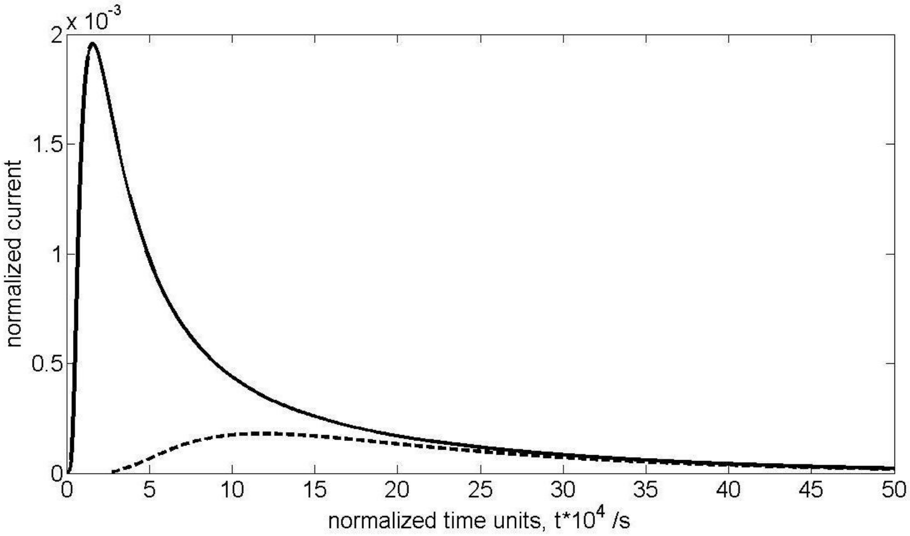

Figure 3: Tunnel junction current as a function of time. The solid line corresponds to the tunneling through the right tunnel junction, while the dashed line corresponds to tunneling through the left tunnel junction.

Figure 1 shows the schematic of the SCEB with two junctions, along with the corresponding dimensions used in this study. The absorber length was set at 13.5 µm. This includes the two junctions at each end of the absorber, each with a length of 0.60 µm. These dimensions correspond to the dimensions used in the previous study of cold-electron bolometers (Agulo et al. 2004).

We followed the parameters used by Ejrnaes et al. (2005) since the junctions used in the SCEB structure are practically the same as those in the DROID structure. The model would already take into account what would happen if the structure dimensions were shrunk. The parameters used are: the diffusion constant, $D = 60\ cm^2\ s^{-1}$, the uniform constant loss rate, $\gamma_{loss} = 10^4\ s^{-1}$, the rate of excess quasiparticle removal from the absorber through the tunnel junction to the electrode, $\gamma_{loss} = 1.43 \times 10^{-6}\ s^{-1}$, and the diffusion length for aluminum, $\Lambda = 775\ \mu m$. The length of the SCEB absorber used in this simulation was about 1.7% of that of the DROID absorber.

Figure 2 shows the quasiparticle density over the whole length of the absorber as a function of time for different times. The unit of time is related to the rate of quasiparticle loss, γ_{loss}, and is given by $\tau = t/10^4\ s^{-1}$. Without considering the differences in width and thicknesses for the SCEB and the DROID, due to the much smaller length, the number of particles available that could participate in the quasiparticle generation is correspondingly decreased.

The effect of the small absorber volume can also be seen in Figure 3. In the simulation, the photon was assumed to appear at a distance of a fourth of the absorber length closer to the right tunnel junction, i.e. at $x = +3.75$. As the quasiparticle density decreases, current is observed through each of the tunnel junctions. More current is observed through the right tunnel junction, since it is closer to where the photon hit the absorber. There is no current saturation, as would be initially thought for a small absorber being bombarded by highly energetic photons. In large volume absorbers, a lot of quasiparticles absorb the photon energy. For small volume absorbers, only a relatively small number of quasiparticles participate in the absorption process. This would result in a small current, dissipating at a fast rate through the tunnel junctions. This translates to a fast response time of the bolometer device, which is very favorable for microwave sensors. As can be seen in the figure, the SCEB has already dissipated all the absorbed energy after 50 time units. The faster the response time, the more photons the device can read and the more information regarding the microwave radiation is obtained.

Let us analyze the results further. The SCEB operation requires the use of dissimilar superconductors, i.e., two superconductors with different superconducting gap energies. In contrast, the DROID uses two similar superconductors. In the SCEB, the absorber material is the superconductor with the lower energy gap, Δ_1, while the electrode material is the superconductor with the higher energy gap, Δ_2. Titanium and aluminum are good material choices for absorber and electrode materials, respectively. Aluminum has a gap of 180 μeV, while titanium has a gap of 49 μeV.

The tunneling rate for two superconductors is proportional to the number of particles that participate in the tunneling and to the number of available energy states where the particles can go to (Tinkham 1996). Thus, the tunneling rate is independent of whether the tunneling is due to two similar, or to two dissimilar, superconductors. Therefore, the use of the value for the ratio of tunneling rate to tunneling loss ($\gamma_{tunn}/\gamma_{loss} = 143$) is justifiable. In the case of a small absorber, where the coupling of the electrons in the absorber and the phonons in the substrate should be much smaller than that for STJs and DROIDs, the tunneling loss would be smaller, and the ratio of the tunneling rate to the tunneling loss would increase. The model suggests that increasing the ($\gamma_{tunn}/\gamma_{loss}$) ratio ten times would not lead to more quasiparticles and higher current, and to an insignificant increase in the response time.

The SCEB would typically be biased at a voltage where the junction resistance would match the impedance of the read-out electronics. Impedance matching maximizes the transfer of power from the absorber through the tunnel junction. This is achieved by biasing the tunnel junction just above the difference voltage of the two superconductors, i.e., $V_{bias} \approx (\Delta_2 - \Delta_1)/e$. At this bias voltage, it is relatively easy to match the impedance of the tunnel junction (and therefore of the bolometer) to that of the read-out electronics.

CONCLUSION

The use of a small volume for an absorber is ideal if the response characteristics of a microwave radiation bolometer are to be improved. With a decrease in volume, the response time decreases to 50 time units without any saturation of the tunnel junction current. Thus, the superconducting cold-electron bolometer promises to be a faster device and can more easily be integrated to the read-out electronics.

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CONFLICTS OF INTEREST

There are no conflicts of interest in this study.

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