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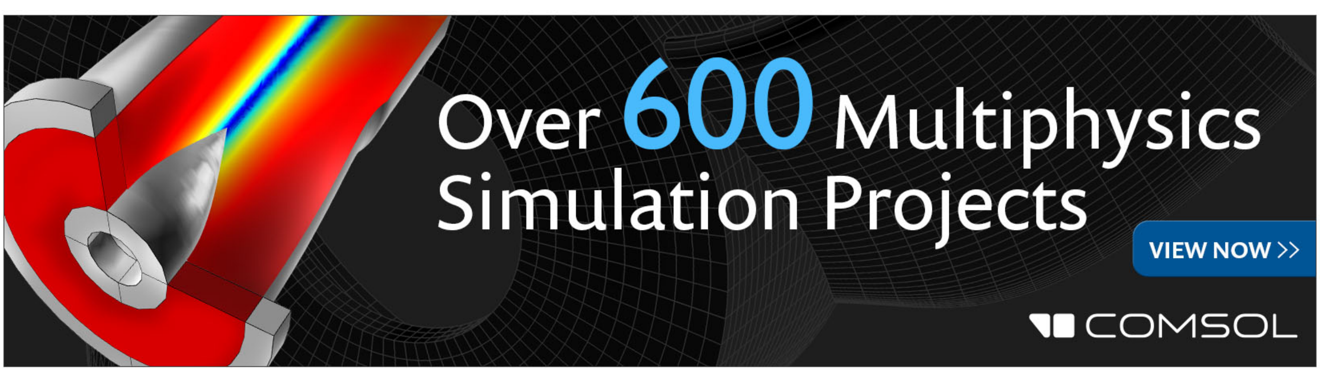

Nonequilibrium dynamic conductivity of superconductors: An exploitable basis for high-energy resolution x-ray detectors

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A new design for high-energy radiation/particle detectors is presented. The nonequilibrium response of a superconductor to the absorption of the incident quanta is sensed by electromagnetic measurements of the altered dynamic conductivity. Microwave absorption may be used to amplify the signal. Such a detector will provide better energy resolution than semiconducting charge-collection devices once the statistical resolution limit is reached.

In the realms of both high-energy astrophysics and instrumentation for laboratory materials analysis, *a niche market exists* for energy sensors in the 1–15 keV energy range.[1] Superconducting tunnel junctions (STJ) are being extensively explored[2–7] as nonequilibrium electronic-excitation sensors. The basic argument is that all previous classes of nonequilibrium high-energy detectors have succeeded in reaching the limit, where their energy resolution is limited by the statistics of excitation production. This is expressed by the equation: $\delta E \simeq 2.355(F\epsilon E)^{1/2}$, where F is the Fano factor, typically <1,[8] E is the initial absorbed energy, ϵ is mean energy cost per excitation produced, and δE is the energy uncertainty of the measurement. The argument that sensing quasiparticle excitations in a superconductor provides a way of achieving exceptional energy resolution revolve around the fact that ϵ is 10^3 smaller in a superconductor than in a semiconductor. In addition, F has been calculated to be 0.17 (Ref. 4) reflecting incomplete independence of the energies of the final excitations.

For the STJ detectors, the tunnel current provides a mechanism for enumerating the excess quasiparticle population. However, so far the experimental efforts[9–11] have had difficulty reaching the stage where the energy resolution scales in the incident energy in this quasiparticle production limited manner. As discussed in Ref. 12, some of this discrepancy may relate to the statistics of the commonly utilized multiple tunneling. However, in addition, consistent with the Rothwarf–Taylor equations in the modeling, it has been assumed that each quasiparticle makes an equal contribution to the tunneling current. This assumption is herein shown to be incorrect. Instead, the single-electron excitations distribution function, weighted by the BCS density of states $u_\epsilon = |\epsilon|\theta(\epsilon^2-\Delta^2)(\epsilon^2-\Delta^2)^{-1/2}$ squared, determines the current. This causes the measurement to be most sensitive to the lowest energy excitations.

The dynamic conductivity of a simple superconducting film is determined by an identical dependence on the quasiparticle distribution function. In this letter we explore the consequences of this fact. *Alternative designs* for no equilibrium superconducting detectors based on conductivity measurements may be feasible. The presentation starts with an estimate of the magnitude of the conductivity shift expected from 10 keV photon in a sensor pixel that has been sized to allow signal readout via microwave reflection measurements. We then describe a mechanism by which the signal may be amplified before it is detected.

Normally STJ detectors are operated at voltages well below the gap edge. This is done to minimize the shot noise associated with the bias current. However it also insures that extra Joule heating associated with the event is insufficient to "latch" the detector. For such small bias voltages, the expression for the quasiparticle current passing through the barrier is[13–20]

$$I_{qp} = (1/2R_N)\int_{-\infty}^{\infty} d\epsilon\; u_\epsilon u_{\epsilon-V}[(1-2n_\epsilon)\,\mathrm{sign}\,\epsilon - (1-2n_{\epsilon-V})\,\mathrm{sign}(\epsilon-V)]. \quad (1)$$

In Eq. (1), R_N is the barrier resistance, and $e=\hbar=1$. In deriving Eq. (1) the materials on each side were assumed to have the same energy gaps. Moreover, the shapes of the excess quasiparticle distribution functions were assumed to be the same except for the constant shift of the energy by the bias voltage value V. These assumptions are correct when the junction is fully symmetric in its elemental constituents and the energy density resulting from the event to be detected is the same in each layer. The latter condition is met when ionizing particles pass through the junction without substantially slowing or when the tunneling time is substantially shorter than the process of evolution of the excess quasiparticles. This assumption was adopted in earlier discussions[20] of the use of tunnel junctions as detectors of visible and acoustic energy and more recently of x rays.[21] STJ detectors utilizing multiple tunneling[4] will also meet this condition once the energy has become homogenized.

As was stated above, we are to consider the case $V \ll \Delta$. Expanding the integrand in Eq. (1), one comes to the expression for the junction differential conductivity $\sigma = \lim(I/V)$, $V \to 0$ (in the units $2/R_N$):

$$\sigma = \int_{-\infty}^{\infty} u_\epsilon^2 (\partial n_\epsilon / \partial \epsilon) d\epsilon. \quad (2)$$

In the case of normal metals ($\Delta = 0,\ u_\epsilon = 1$), the integral Eq. (2) is finite. Substitution of the equilibrium function $n_\epsilon = n_\epsilon^0 = [1 + \exp(|\epsilon|/T)]^{-1}$ yields the usual Ohm law. In the case of superconductors, by contrast, the integral Eq. (2) diverges logarithmically even when the equilibrium functions are substituted. The divergence is removed in reality by the factors that smear the BCS density of states. The energy damping $\gamma \sim T_c^3/\omega_D^2$, connected with the finite lifetime of the excitations, may serve as such a factor. The presence of kernel u_ϵ^2 in Eq. (2) acts to strongly enhance the contribution of gap edge quasiparticles to the observed values of σ.

The *dynamic conductivity* $\sigma(\omega)$ of a bulk superconductor may be derived from TDGL equations,[22] when $\omega \ll \gamma$, or from the Mattis–Bardeen expression[23] for the frequency range $\gamma < \omega < 2\Delta$, In units of σ_N, the expression is identical to Eq. (2). Thus the response of the dynamic conductivity of a superconducting film to the passage of high-energy particles is formally the same as the response of the tunnel current in a nonequilibrium tunnel junction. Whether this response can be used as the basis of a detector is thus dependent on finding an experimental method of registration in which the change in the dynamic conductivity has sufficient accuracy. While quasioptical readout is imaging herein,[24] any technique in the frequency range up to terahertz ($2\Delta/\hbar$) is a candidate.

A quantitative estimate of response for the predicted effect is desirable. For definiteness we consider the case of Al films. Assume an initial event deposits 10 keV impulsively into a superconducting film (Fig. 1, inset a). This creates a ''fireball'' of excitations in the electronic and ionic systems of the metal which rapidly cascades downward to the 1 meV scale of energies and becomes a mere ''hot spot.'' In the hierarchy of times which characterize this process in the superconductor, the largest is the time the excess excitations, the quasiparticles, spend almost elastically diffusing before their disappearance by annihilation into Cooper pairs. This time is quite long (usually estimated as 10^{-5}–10^{-6} s). For sufficiently thin and homogeneous films, the energy quickly becomes uniformly distributed within the film thickness. The smaller the sample volume, the higher the concentration of excess quasiparticles.

Our *scheme of event registration* is shown schematically in Fig. 1. The lateral dimensions of the sample dimensions d must be comparable to or larger than the wavelength of electromagnetic radiation λ, which is used to register the excursions of conductivity to achieve a highly reproducible response to the excess quasiparticle density. For Al this yields to $d > 300\ \mu$. We may assume the Al film functions only as a trapping layer. Another superconductor will play the role of the x-ray absorber [see insert (a) to Fig. 1]. Thus the thickness of Al film can be chosen as small as the skin depth at the probing frequency, i.e., $\delta \sim 10^{-6}$ cm. If the gap of a superconductor has a value $2\Delta \sim 0.3$ meV, then the order of magnitude number of quasiparticles at the final stage of evolution is $> 10^8$. For pixels of the minimal cross section d^2, the excess quasiparticle concentration will thus be of order of

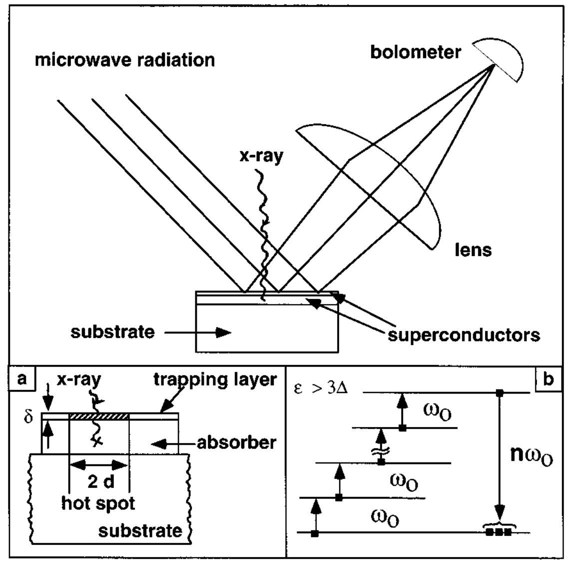

FIG. 1. Detector design. Superconducting films (including trapping layer on the top and absorber underneath) are deposited on substrate. Details are in the insert (a), the ''hot spot'' is dashed. Incident radiation has a frequency $\omega_0 < 2\Delta$ (the gap of underlying absorber is higher than Δ of the trapping layer). Microwave radiation may serve both for ''readout'' and for amplification. Insert (b): intrinsic amplification of the detector response. Successive absorption of n photons moves an existing quasiparticle to an energy level $\epsilon > 3\Delta$, then it may be splitted into three low-lying quasiparticles, ready to continue this process. Only two steps are enough in $\Delta < \omega_0 < 2\Delta$ case.

$\delta N \sim 10^{17}$ cm^{-3}. In superconductors, the enhancing factor of u_ϵ^2 causes an order of magnitude larger response than in normal metals. Compared to the normal metal conductivity the deviation of conductivity will be of the level $\delta\sigma_S/\sigma_N \sim 10^{-5}$. At $T < T_c$, σ_s may be much smaller than σ_N: substituting n_ϵ^o into Eq. (2), one can obtain $\sigma_S/\sigma_N \sim 10^{-3}$ at $T \sim 0.1 T_c$, so the relative deviation is $\delta\sigma_S/\sigma_S \sim 1\%$. This value is a measurable one,[24] though it must be measured with an appropriate precision.

This analysis clearly indicates that detecting the change in σ in order to measure the energy of single x-ray quantum with high accuracy will not be an easy task. However, the signal may be enhanced by *intrinsic amplification* prior to detection. Such an amplification may result from the possibility of ''breeding'' of the single-electron excitations via the series absorption of low energy photons of external radiation. This mechanism was first described by Eliashberg *et al.*[25,26] and then applied[27] to microscopic description of heating process in superconductors by intense UHF fields, previously treated phenomenologically.[28] The idea of mechanism is based on the calculations demonstrating that at the frequency range $\gamma < \omega_0 < 2\Delta$, simultaneous multiquanta absorption by the pairs has a probability that scales with $(\gamma/\omega_0)^{2n}$.[25] For $\omega_0 \gg \gamma$, it is thus a highly improbable process. At such frequencies, single photons cannot also create additional excitations from the pair condensate because their energy is insufficient. However for intense fields successive single-quantum processes of the type shown in insert (b) to Fig. 1 are possible starting from pre-existing electronic excitations. When the particle acquires the energy $\epsilon > 3\Delta$, 3 single-electron excitations result from a collision with the Cooper condensate. Our calculations show that this happens at $\alpha > \beta\gamma$. Here $\alpha = 2(e/c)^2 D A_\omega A_{-\omega}$ is the parameter, which characterizes the coupling of electromagnetic radiation, described by the vector-potential A_ω, with the metal. The dimensionless parameter b characterizes the reciprocal intensity of electron–electron intercollisions compared with that of electron–phonon collisions: $\beta \sim \epsilon_F T/\omega_D^2$ at $T \sim T_c$, and $\beta \sim \epsilon_F \Delta/\omega_D^2$ at $T \ll \Delta$. $D = l v_F$ is the diffusion coefficient of normal electrons. Restoring $\hbar$ to the expressions, we can estimate $H_{\omega 0} \sim (\hbar \omega_0/e)(\alpha/D)^{1/2}$ for the threshold amplitude of electromagnetic field $H = H_{\omega 0} \cos \omega_0 t$, which may cause the ''breeding.'' Its numerical value follows to be 10^{-4} Oe, if $\gamma \sim 10^9\ \mathrm{s}^{-1}$, $l = 10^{-5}$ cm, $\omega_0 \sim 10$ GHz, and $\beta \sim 1$. The amplification is proportional to the exponential of the difference $(\alpha - \beta\gamma)$, so the process may be very fast with the characteristic time scale estimated as $(\beta\gamma)^{-1}$.

Thus nonlinear absorption of intense electromagnetic field, previously recognized as the very negative factor at the superconductivity stimulation process,[29] may have very positive consequences for superconducting particle detection, amplifying the number of excess quasiparticles created initially by the high-energy quantum and simplifying the detection.

In conclusion, we have demonstrated that the behavior of dynamic conductivity of nonequilibrium superconducting thin film in response to a high-energy event is no less sensitive to the resultant excess excitation than is the tunneling current of STJ detectors. Subsequent enhancement of the excess quasiparticles population by ''breeding'' via additional microwave pumping opens the possibility of detecting the conductivity response via reflectivity measurements in trapping layer structures. The simplicity of proposed scheme may open additional advances both in energy resolution of detectors and in their spatial resolution.

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[1] Current and previous works of the many groups world wide actively developing STJ detectors can be found, e.g., in J. Low Temp. Phys. **93** (1993); *Proceedings of the Workshop X-ray Detection by Superconducting Tunnel Junctions*, edited by A. Barone, R. Cristiano, and S. Pagano (World Scientific, Singapore, 1990); *Low Temperature Detectors for Neutrinos and Dark Matter IV,* edited by N. E. Booth and G. L. Salmon (Editions Frontiers, Gif-sur-Yvette, 1990).
[2] G. H. Wood and B. L. White, Appl. Phys. Lett. **15**, 237 (1969).
[3] M. Kurakado and H. Mazaki, NIM **185**, 149 (1981).
[4] M. Kurakado, NIM **196**, 275 (1982).
[5] N. E. Booth, Appl. Phys. Lett. **50**, 1986 (1986).
[6] N. Rando, A. Peacock, A. Van Dordrecht, C. Foden, R. Englhardt, B. G. Taylor, P. Gare, J. Lumley, and C. Pereira, NIM A **313**, 173 (1992).
[7] D. Van Vechten and K. S. Wood, Phys. Rev. B **43**, 12852 (1991).
[8] U. Fano, Phys. Rev. **72**, 26 (1947).
[9] C. L. Foden, N. Rando, A. Peacock, and A. J. Van Dordrecht, Appl. Phys. **74**, 6774 (1993).
[10] A. Matsumura, T. Takahashi, and M. Kurakado, NIM A **239**, 227 (1993).
[11] C. A. Mears, S. E. Labov, and A. T. Barfknecht, Appl. Phys. Lett. **63**, 2961 (1993).
[12] D. J. Goldie, P. L. Brink, C. Patel, N. E. Both, and G. L. Salmon, Appl. Phys. Lett. **64**, 3169 (1994).
[13] B. D. Josephson, Phys. Lett. **1**, 251 (1962).
[14] N. R. Werthamer, Phys. Rev. **147**, 255 (1966).
[15] A. I. Larkin and Yu. N. Ovchinnikov, Zh. Eksp. Teor. Fiz. **51**, 1535 (1966) [Sov. Phys. JETP **24**, 1035 (1967)].
[16] A. V. Svidzinskii and V. A. Slyusarev, Zh. Eksp. Teor. Fiz. **51**, 201 (1966) [Sov. Phys. JETP **24**, 120 (1967)].
[17] S. B. Nam, Phys. Rev. **156**, 470 (1967).
[18] R. E. Harris, Phys. Rev. B **10**, 84 (1974).
[19] A. M. Gulyan and G. F. Zharkov, Zh. Eksp. Teor. Fiz. **89**, 156 (1985) [Sov. Phys. JETP **62**, 89 (1985)].
[20] J.-J. Chang and D. J. Scalapino, Phys. Rev. Lett. **37**, 522 (1976).
[21] A. Zehnder (unpublished).
[22] A. M. Gulyan, G. F. Zharkov, and G. M. Sergoyan, Zh. Eksp. Teor. Fiz. **92**, 190 (1987) [Sov. Phys. JETP **65**, 107 (1987)].
[23] D. C. Mattis and J. Bardeen, Phys. Rev. **111**, 412 (1958).
[24] B. P. Gorshunov, I. V. Fedorov, G. V. Kozlov, and A. A. Volkov, Semicond. Sci. Technol. **87**, 17 (1993).
[25] G. M. Eliashberg, Zh. Eksp. Teor. Fiz. **61**, 1254 (1971) [Sov. Phys. JETP **34**, 668 (1971)].
[26] B. I. Ivlev, S. G. Lisitsyn, and G. M. Eliashberg, J. Low Temp. Phys. **10**, 449 (1972).
[27] A. M. Gulian and G. F. Zharkov, J. Low Temp. Phys. **48**, 125 (1982).
[28] U. Eckern, A. Schmid, M. Schmutz, and G. Shon, J. Low Temp. Phys. **36**, 643 (1979).
[29] V. M. Dmitriev, V. M. Gubankov, and F. Ya Nad', *Nonequilibrium Superconductivity*, edited by D. N. Langenberg and A. I. Larkin (North Holland, Amsterdam, 1986), Chap. 5.

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