

# Intrinsic superconducting radiation detector

M. I. Flik, Z. M. Zhang,<sup>a)</sup> and K. E. Goodson

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 19 August 1992; accepted for publication 4 March 1993)

A novel radiation detector, the Intrinsic Superconducting Radiation Detector (ISRD), is proposed. It employs the temperature dependence of the critical current of high  $T_c$  superconducting films to determine the detector temperature change caused by incident radiation and operates almost exclusively in the superconducting state. The ISRD has the potential to be a phonon-noise-limited thermal detector.

Conventional bolometers based on superconducting materials employ the rapid change of the electrical resistance with temperature in the superconducting-to-normal state transition.<sup>1</sup> Since these bolometers operate near the midpoint of the transition region, Joule heating and Johnson noise are unavoidable. McDonald<sup>2</sup> and Sauvageau *et al.*<sup>3</sup> employed the temperature dependence of the kinetic inductance of superconducting niobium microstripline to build highly sensitive radiometers operating entirely in the superconducting state. The critical current-temperature relation can also be employed for radiation detectors.<sup>4,5</sup> In this letter, we propose a superconducting radiation detector based on the temperature dependence of the critical current of high  $T_c$  superconducting films. It operates below  $T_c$  and, therefore, makes Joule heating and Johnson noise negligibly small.

The critical current  $I_c$  of a superconductive bridge is the maximum dc electrical current it can carry without Joule heating. In practice, the measured critical current is the current which yields a voltage equal to a voltage criterion. The critical current decreases with increasing temperature for temperatures less than  $T_c$  and is zero at  $T_c$ . The temperature of the detector can be determined by measuring  $I_c$ .<sup>4</sup> Figure 1 is a schematic of the Intrinsic Superconducting Radiation Detector (ISRD). The detector element is a superconducting film deposited on a substrate. The incident radiation power  $P$  is modulated with an angular frequency  $\omega$ . The time-dependent temperature difference between the detector and the heat sink is  $\Delta T(t)$ . The thermal time constant of the detector must be much smaller than the time period of modulation in order for the detector to reach a steady temperature during each period. After a steady state is achieved, the bias current  $I$  is increased from zero to the critical current by varying the source voltage  $V_s$  across the resistance  $R$  of the electrical circuit. When the voltage across the superconducting film  $V$  exceeds a voltage criterion  $V_c$ , the current  $I(=I_c)$  is recorded and the voltage  $V_s$  is then reduced to zero. Figure 2 shows the incident radiation power, the temperature, the current, and the voltage across the superconducting film as functions of time. Figure 3 illustrates the operating points of the ISRD. Unlike the resistance bolometers which are always resistive, the ISRD works at or below the critical

current for a given temperature. As a result, Joule heating and Johnson noise are negligible in the sensing bridge, allowing this detector to operate at the phonon-noise limit.

Modeling the film-substrate composite as a bulk material of uniform temperature yields

$$\alpha P = C \frac{d\Delta T(t)}{dt} + G\Delta T(t), \quad (1)$$

where  $\alpha$  is the absorptance,  $C$  is the heat capacity of the film-substrate composite, and  $G$  is the thermal conductance between the detector and the heat sink. The solution to Eq. (1) for  $\Delta T(0) = 0$  is

$$\Delta T(t) = \frac{\alpha P}{G} \left[ 1 - \exp\left(-\frac{t}{\tau_T}\right) \right], \quad (2)$$

where  $\tau_T = C/G$  is the thermal time constant. The steady temperature  $\Delta T(t \gg \tau_T)$  is  $\alpha P/G$ . Note that  $\Delta T(t)$  reaches 99.995% of its steady-state value for  $t = 10 \tau_T$ . In the present design, steady state must be achieved within a half-period,  $\pi/\omega$ , and the thermal time constant  $\tau_T$  must satisfy  $10 \tau_T < \pi/\omega$ .

The detector responsivity is defined as the output current per unit radiation power. The responsivity  $S$  of the ISRD is

$$S = \left| \frac{dI_c}{d\Delta T} \frac{d\Delta T}{dP} \right| = \frac{\alpha}{G} \frac{dI_c}{d\Delta T}. \quad (3)$$

The critical current decreases almost linearly with increasing temperature if the temperature is not too close to the

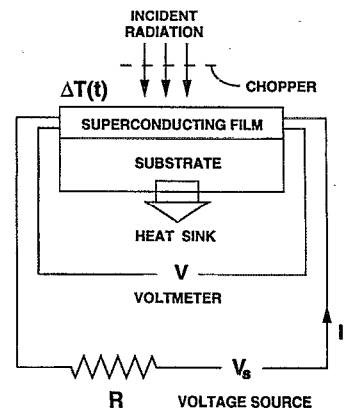


FIG. 1. Schematic of the ISRD.

<sup>a)</sup>Current address: Radiometric Physics Division, National Institute of Standards and Technology, Gaithersburg, MD 20899.

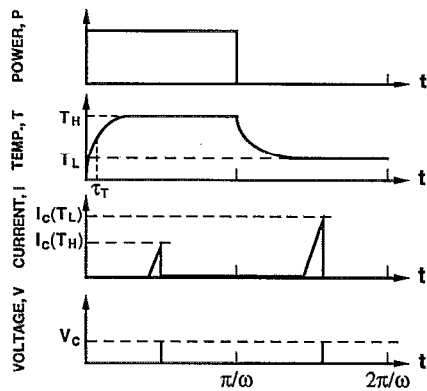


FIG. 2. Response curves of the ISRD.

critical temperature.<sup>6-8</sup> High-quality epitaxial  $\text{YBa}_2\text{Cu}_3\text{O}_7$  films with critical current density exceeding  $10^6 \text{ A cm}^{-2}$  are available not only on  $\text{LaAlO}_3$ ,  $\text{SrTiO}_3$ ,  $\text{MgO}$ , and sapphire substrates,<sup>7-9</sup> but also on Si substrates with *YSZ* buffer layers.<sup>10</sup> The dimensions of the superconducting film considered in the present design are  $200\text{-}\mu\text{m}$  long,  $25\text{-}\mu\text{m}$  wide, and  $0.3\text{-}\mu\text{m}$  thick. If  $J_c(77 \text{ K}) = 2 \times 10^6 \text{ A cm}^{-2}$  and  $T_c = 90 \text{ K}$ , the critical current is  $0.15 \text{ A}$  and  $|dI_c/d\Delta T|$  is approximately  $10 \text{ mA K}^{-1}$ . Small values of the conductance  $G$  and large values of the absorptance  $\alpha$  improve the responsivity.

The methods, criteria, and accuracy for the critical current measurement of high  $T_c$  superconductors were discussed by Goodrich<sup>11</sup> and Goodrich and Bray.<sup>12</sup> Typical electric field criteria are between  $10^{-5}$  and  $10^{-3} \text{ V m}^{-1}$  and are limited by the voltmeter sensitivity. The  $V$ - $I$  characteristic close to the critical point ( $I_c$ ,  $V_c$ ) can be approximated by the power-law<sup>11</sup>

$$V/V_c = (I/I_c)^n, \quad (4)$$

where  $n$  measures the abruptness of the transition and ranges from 20 to 60 for conventional superconductors. A value for  $n$  of approximately 45 was obtained by Ekin<sup>13</sup> for polycrystalline bulk  $\text{YBa}_2\text{Cu}_3\text{O}_{7-8}$  at  $76 \text{ K}$  without a magnetic field. This indicates that a 5% error in the measured voltage will only cause an error of 0.1% in the critical current.

The maximum Joule heating power is  $V_c I_c$ . The difference between the maximum Joule heating power without and with a power  $P$  is  $V_c \Delta I_c = V_c P S$ . Using a voltage criterion of  $100 \text{ nV}$  and taking the responsivity  $S = 1000 \text{ W A}^{-1}$ , the Joule heating power is  $15 \text{ nW}$  and the relative error in the power measurement caused by the Joule heating is  $V_c \Delta I_c / P = 10^{-4}$ . Hence, the error caused by Joule heating is negligibly small.

The accuracy of the ramp method for the critical current measurement may be affected by inductive voltage.<sup>11</sup> Phelan *et al.*<sup>14</sup> measured the ac impedance of a superconducting Bi-Sr-Ca-Cu-O bridge and observed that, for frequencies below  $100 \text{ kHz}$ , the impedance is zero for current densities as high as one-tenth the dc critical current density. Assuming that the current density is increased from zero to a critical current density of  $10^6 \text{ A cm}^{-2}$  in  $1 \text{ ms}$ , the inductive electric field estimated using the first London

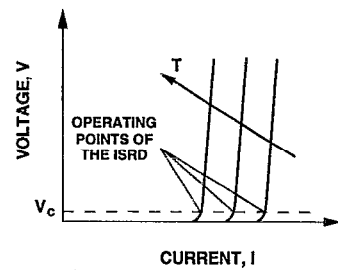


FIG. 3. Operating points of the ISRD.

equation is of the order of  $10^{-7} \text{ V m}^{-1}$ , which is much less than the electric field criterion. Hence, the effect of inductive voltage in the superconductive bridge is negligible. Another issue which may affect the measurement accuracy is the motion of the magnetic flux vortices. It must be investigated whether these will result in an error in the voltage measurement for a rapid increase of current and whether the flux motion will introduce hysteresis in repeating critical current measurements.

The noise equivalent power (NEP) can be broken down into components of Johnson noise, phonon noise, photon noise, and  $1/f$  noise. The combined NEP is<sup>1,15</sup>

$$\text{NEP} = (\text{NEP}_{\text{Johnson}}^2 + \text{NEP}_{\text{phonon}}^2 + \text{NEP}_{\text{photon}}^2 + \text{NEP}_{1/f}^2)^{1/2}. \quad (5)$$

Since the ISRD operates when the current just exceeds the critical current, the resistance and the voltage drop inside the film is neglected. The resistance of the trigger voltmeter can be large enough to be considered an open circuit. The Johnson noise due to the fluctuation of the resistance  $R$  is

$$\text{NEP}_{\text{Johnson}}^2 = 4k_B T_a^2 / (RS^2), \quad (6)$$

where  $k_B$  is Boltzmann constant and  $T_a$  ( $\sim 300 \text{ K}$ ) is the temperature at which the electrical circuit is operated. High values of  $S$  and  $R$  minimize the Johnson noise.

Phonon noise is due to the temperature fluctuation of the detector element

$$\text{NEP}_{\text{phonon}}^2 = 4k_B T_e^2 G / \alpha^2, \quad (7)$$

where  $T_e$  ( $\sim 77 \text{ K}$ ) is the heat sink temperature. For a background with a blackbody temperature of  $T_b$  and cutoff frequencies of  $\nu_1$  and  $\nu_2$ , the photon noise due to the fluctuation of the incident power is

$$\text{NEP}_{\text{photon}}^2 = \frac{4\pi\alpha A \sin^2 \theta (k_B T_b)^5}{c_0^2 h^3} \int_{x_1}^{x_2} \frac{x^4 e^x dx}{(e^x - 1)^2}, \quad (8)$$

where  $c_0$  is the speed of light in vacuum,  $h$  is Planck's constant,  $A$  is the detector receiving area,  $\theta$  is the half-angle of the cone through which the background radiation is received, and  $x_1 = h\nu_1/k_B T_b$  and  $x_2 = h\nu_2/k_B T_b$  are the reduced photon frequencies.

There are other noise components, such as noise due to contact resistance, modulation, and material defects.<sup>16</sup> Since these noise components are generally inversely proportional to the modulation frequency  $f$ , they are called  $1/f$  noise. The NEP of  $1/f$  noise has the form

$$\text{NEP}_{1/f}^2 = C_0 I^\beta / (S^2 f^\gamma), \quad (9)$$

where  $\gamma$  ( $\sim 1$ ),  $\beta$  ( $\sim 2$ ), and  $C_0$  are experimentally determined coefficients.

The  $1/f$  noise for relatively low bias currents near the critical temperature has been studied by several groups.<sup>17-19</sup> In contrast, the  $1/f$  noise of high-quality superconducting films below the critical temperature for a current just in excess of the critical current, i.e., the operating point of the ISRD, has not been reported. This noise must be determined.

The optimum design of the ISRD requires the minimization of both  $G$  and  $\tau_T$ . It is therefore necessary to make the heat capacity as small as possible. The heat capacity of the film-substrate composite is

$$C = (\rho c A d)_{\text{substrate}} + (\rho c A d)_{\text{film}}, \quad (10)$$

where  $\rho$  is the density,  $c$  the specific heat, and  $d$  the thickness of film and substrate, respectively. Since the film thickness is usually less than  $0.5 \mu\text{m}$ , its heat capacity is negligible in comparison with that of the substrate. The heat capacity per unit volume of sapphire, MgO, and silicon is approximately  $0.4 \text{ J cm}^{-3} \text{ K}^{-1}$  at 77 K, and that of  $\text{SrTiO}_3$  is  $1.0 \text{ J cm}^{-3} \text{ K}^{-1}$ . The value of  $0.4 \text{ J cm}^{-3} \text{ K}^{-1}$  is used in the present design. The substrate thickness is assumed to be  $20 \mu\text{m}$ .<sup>20</sup> The area of the superconducting film is  $A = 200 \times 25 \mu\text{m}^2$ . The heat capacity  $C$  is calculated to be  $4 \times 10^{-8} \text{ J K}^{-1}$ . If the modulation frequency is 5 Hz, a thermal time constant of  $\tau < 10 \text{ ms}$  is required for the detector to reach a steady state in each half-period. A thermal conductance  $G = 5 \times 10^{-6} \text{ W K}^{-1}$  is chosen in the present design, which will yield a time constant  $\tau = 8 \text{ ms}$ . Small heat capacity, good thermal isolation, and high-quality epitaxial films can be achieved with silicon micro-fabrication technology.<sup>21,22</sup> The resistance of the electronic circuit is chosen to be  $1000 \Omega$ . In the present design, the absorptance  $\alpha$  is assumed to be 0.5. The absorptance depends strongly on the wavelength of the incident radiation and film thickness.<sup>23</sup>

The calculated responsivity is  $1000 \text{ A W}^{-1}$ . The photon noise of  $2 \times 10^{-13} \text{ W Hz}^{-1/2}$  for a 300 K background with  $\theta = 30^\circ$  and the Johnson noise of  $4 \times 10^{-15} \text{ W Hz}^{-1/2}$  are much less than the phonon noise of  $2.6 \times 10^{-12} \text{ W Hz}^{-1/2}$ . If  $1/f$  noise is assumed to be much smaller than the largest of the other noise components, the detector will work at the phonon noise limit. The combined NEP is  $2.6 \times 10^{-12} \text{ W Hz}^{-1/2}$ , and the detectivity  $D^* = \sqrt{A}^{1/2} / \text{NEP}$  is  $2.7 \times 10^9 \text{ cm Hz}^{1/2} \text{ W}^{-1}$ . The NEP is comparable with that estimated for the high  $T_c$  superconducting microbolometer with a modulation frequency of 10 kHz.<sup>24,25</sup> The ISRD has an advantage over the microbolometer for low modulation frequencies. The  $D^*$  of the ISRD is one order of magnitude higher than that of commercial pyroelectric detectors.

In summary, a novel high  $T_c$  superconducting radiation detector is proposed, which operates at temperatures below  $T_c$  and has the potential to work at the phonon-noise limit. The  $1/f$  noise for currents just above the critical current, the accuracy of the critical current measurement using a ramp technique, and the possible existence of hysteresis due to magnetic flux motion must be investigated experimentally.

The authors wish to thank Professor J. L. Smith, Jr., Professor T. P. Orlando, Professor R. P. Huebener, Dr. Ph. Lerch, Dr. R. J. Keyes, F. E. Mullen, and C. A. Bang for helpful discussions. This work was supported by the C. S. Draper Laboratory, Cambridge, MA, under Contract No. DL-H-418480. K.E.G. acknowledges the support of the U.S. Office of Naval Research.

- <sup>1</sup>P. L. Richards, J. Clarke, R. Leoni, Ph. Lerch, S. Verghese, M. R. Beasley, T. H. Geballe, R. H. Hammond, P. Rosenthal, and S. R. Spielman, *Appl. Phys. Lett.* **54**, 283 (1989).
- <sup>2</sup>D. G. McDonald, *Appl. Phys. Lett.* **50**, 775 (1987).
- <sup>3</sup>J. E. Sauvageau, D. G. McDonald, and E. N. Grossmann, *IEEE Trans. Magn.* **MAG-27**, 2757 (1991).
- <sup>4</sup>B. I. Verkin, B. B. Banduryan, A. V. Bondarenko, V. G. Efremenko, V. A. Konovodchenko, M. A. Obolenskii, and G. V. Shustakova, *Sov. J. Low Temp. Phys.* **14**, 387 (1988).
- <sup>5</sup>D. Robbes, P. Langlois, C. Dolabdjian, D. Bloyet, J. F. Hamet, and H. Murray, *IEEE Trans. Appl. Supercond.* **AS-3**, 2120 (1993).
- <sup>6</sup>A. Frenkel, C. C. Chang, E. Clausen, T. Venkatesan, P. S. D. Lin, X. D. Wu, A. Inam, and B. Lalevic, *J. Mater. Res.* **5**, 691 (1990).
- <sup>7</sup>X. G. Qiu, C. G. Cui, S. L. Li, M. X. Liu, J. Li, Y. Z. Zhang, Y. Y. Zhao, P. Xu, L. Li, L. F. Chen, P. F. Chen, N. Li, and G. T. Liu, *J. Appl. Phys.* **70**, 2461 (1990).
- <sup>8</sup>T. Freltoft, H. J. Jensen, and P. Minnhagen, *Solid State Commun.* **78**, 635 (1991).
- <sup>9</sup>G. Gieres, H. Schmidt, K. Hradil, W. Hösler, and R. Seeböck, *Physica C* **185-189**, 2115 (1991).
- <sup>10</sup>D. K. Fork, D. B. Fenner, A. Barrera, J. M. Phillips, T. H. Geballe, G. A. N. Connell, and J. B. Boyce, *IEEE Trans. Appl. Supercond.* **AS-1**, 67 (1991).
- <sup>11</sup>L. F. Goodrich, *Cryogenics* **31**, 763 (1991).
- <sup>12</sup>L. F. Goodrich and S. L. Bray, *Cryogenics* **30**, 667 (1990).
- <sup>13</sup>J. W. Ekin, *Appl. Phys. Lett.* **55**, 28 (1989).
- <sup>14</sup>P. E. Phelan, T. Ohmori, K. Hijikata, and M. Ihara, *Advances in Superconductivity*, edited by H. Hayakawa and N. Koshizuka (Springer, Berlin, 1992), p. 987.
- <sup>15</sup>P. W. Kruse, *Semicond. Sci. Technol.* **5**, S229 (1990).
- <sup>16</sup>R. C. Jones, *Proc. IRE* **47**, 1481 (1959).
- <sup>17</sup>A. E. Khalil, *Solid State Commun.* **80**, 927 (1991).
- <sup>18</sup>J. Hall, H. Hickman, and T. M. Chen, *Solid State Commun.* **76**, 921 (1990).
- <sup>19</sup>J. H. Lee, S. C. Lee, and Z. G. Khim, *Phys. Rev. B* **40**, 6806 (1989).
- <sup>20</sup>S. Verghese, P. L. Richards, K. Char, and S. A. Sachtjen, *IEEE Trans. Magn.* **MAG-27**, 3077 (1991).
- <sup>21</sup>C. A. Bang, M. I. Flik, M. A. Schmidt, and Z. M. Zhang, United States Patent Application, MIT Case No. 5746, Serial No. 07-870,125, 1992.
- <sup>22</sup>T. G. Stratton, B. E. Cole, P. W. Kruse, R. A. Wood, K. Beauchamp, T. F. Wang, B. Johnson, and A. M. Goldman, *Appl. Phys. Lett.* **57**, 99 (1990).
- <sup>23</sup>Z. M. Zhang, B. I. Choi, T. A. Le, M. I. Flik, M. P. Siegal, and J. M. Phillips, *J. Heat Transfer* **104**, 644 (1992).
- <sup>24</sup>Q. Hu and P. L. Richards, *Appl. Phys. Lett.* **55**, 2444 (1989).
- <sup>25</sup>M. Nahum, Q. Hu, P. L. Richards, S. A. Sachtjen, N. Newman, and B. F. Cole, *IEEE Trans. Mag.* **MAG-27**, 3081 (1991).