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DESIGN ANALYSIS OF A HIGH  $T_C$  SUPERCONDUCTING MICROBOLOMETER

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Abstract

We propose an antenna-coupled microbolometer based on the resistive transition of a high  $T_C$  superconducting film as a detector for far infrared and millimeter waves. Such microbolometers can be mechanically stronger, more easily fabricated, and much faster than conventional bolometric infrared detectors. A design analysis shows that a noise equivalent power of  $2.5 \times 10^{-12} \text{ W Hz}^{-1/2}$  is achievable for modulation frequencies up to 100 kHz. The superconducting film must be of high quality with narrow resistive transition and low  $1/f$  noise.

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A high  $T_c$  superconducting bolometer was recently proposed which can potentially be two orders of magnitude more sensitive than any other liquid nitrogen-cooled detector at infrared wavelengths longer than  $20 \mu\text{m}$ .<sup>1</sup> This proposed bolometer is conventional in the sense that the incident radiation is thermalized in a region that is comparable in size to the focal spot which is at least as large as the wavelength. Bolometers for long infrared wavelengths suffer from slow time constants due to the undesirable heat capacity of the substrate which provides the mechanical support for the radiation absorber and the thermometer. To minimize this undesirable heat capacity, very thin substrates ( $\leq 25 \mu\text{m}$ ) can be used but they are difficult to produce and are mechanically fragile.

In this letter we propose a high  $T_c$  superconducting microbolometer whose linear dimensions are small compared with the thermal diffusion length at the chopping frequency. Because of the small size, a high  $T_c$  film deposited directly onto a thick substrate will have small thermal conductance into the bulk of the substrate. Consequently, the sensitivity of the microbolometer can be very good. Also, the heat capacity of the film and of the volume of substrate thermally coupled to it will be small enough that the microbolometer can be quite fast. A room temperature microbolometer, which uses the temperature dependent resistance of a very small Bi film, was described a decade ago.<sup>2</sup> It has an NEP =  $1.6 \times 10^{-10} \text{ WHz}^{-1/2}$  up to several hundred kHz. We estimate that a  $1 \times 5 \mu\text{m}^2$  YBCO microbolometer could have NEP =  $2.5 \times 10^{-12} \text{ WHz}^{-1/2}$  up to 100 kHz. Even better performance may be achievable with smaller film areas. Imaging arrays of microbolometers are much simpler to construct than of

conventional high  $T_c$  bolometers because they can be lithographed directly onto the thick substrate.

At near infrared wavelengths, the diffraction limited focal spot can be made small enough that the incident radiation can be absorbed directly in the microbolometer. At far infrared and submillimeter wavelengths, an antenna can be used<sup>2</sup> to couple radiation into a small area of high  $T_c$  superconducting film. Although the antenna must be at least comparable in size to the wavelength, the dimensions of the region in which the infrared power is thermalized can be much smaller.

Planar lithographed antennas are used to couple both semiconducting and superconducting devices to radiation fields from far infrared to millimeter wavelengths.<sup>3</sup> The short wavelength limit of this technology is not well understood, but response has been demonstrated at  $119 \mu\text{m}$ .<sup>2</sup> The simplest example of such an antenna is the dipole. Alternatively, there is a useful class of broad band antennas, called self-complementary, in which the shape of the regions covered by metal is the same as the shape of the regions of bare dielectric. The simplest such antenna is the  $90^\circ$  bow tie. Others, with more useful antenna patterns include the log-periodic<sup>4</sup> and the spiral.<sup>5</sup> All are very broad band and have a frequency independent real antenna impedance<sup>3</sup>

$$R = 377[2(1+\epsilon)]^{-1/2} \Omega$$

that depends only on the dielectric constant  $\epsilon$  of the substrate. Because the radiation from antennas on dielectric substrates propagates preferentially into the substrate, they are often made on the flat side of a dielectric lens, as is shown in Fig. 1.

The high  $T_c$  film used in the antenna-coupled microbolometer must meet several requirements. In order to thermalize the far infrared energy efficiently, the resistance at the midpoint of the transition must match the resistance of the antenna. Since the typical resistivity of a good quality YBCO thin film is  $\sim 100 \mu\Omega\text{cm}$  just above  $T_c$ , the ratio of length to cross sectional area should be  $\sim 10^6 \text{ cm}^{-1}$  to match a self-complementary antenna on a substrate with  $\epsilon = 10$ . The width of the resistive transition should be narrow so that the voltage responsivity, which is proportional to  $dR/dT$  for a constant current bias, will be large. Also, excess  $(1/f)$  noise in the bolometer must be small. This requires the use of high quality c-axis films.<sup>1</sup> The responsivity of the bolometer will improve as the film area  $A$  is reduced. Successful patterning of films with sub-micron dimensions has been reported.<sup>6</sup> We have chosen a conservative film volume of  $5 \times 1 \times 0.02 \mu\text{m}^3$  for the numerical examples quoted below to avoid excessive low frequency noise, which may scale inversely with film volume.

Because of the large positive temperature coefficient ( $dR/dT > 0$ ) of the film at the bias point near  $T_c$ , the current in the film will distribute itself to make the temperature of the film uniform. Measurements on other metal-dielectric interfaces<sup>7</sup> suggest that the thermal boundary resistance will be negligible at 90 K so that the film temperature will be equal to that of the contiguous substrate. Buffer layers, which can be useful in the preparation of high  $T_c$  superconducting films may, however, enhance this resistance. Following the analysis of ref. 2, the thermal conductance  $G_S$  from the high  $T_c$  superconducting film to the bulk of the substrate can be written as

$$G_S(f) = \kappa_S |\int \nabla T \cdot ds| / \Delta T, \quad (1)$$

where  $\kappa_S$  is the thermal conductivity of the substrate,  $T$  is the position dependent temperature in the substrate,  $\Delta T$  is the temperature difference between the film and the substrate far from the film, and the integral is over the area of the substrate underneath the film. We model the contact between the film and the substrate as a hemisphere of radius  $a$ , so that the heat flux is radial. The temperature of this contact is assumed to be modulated at frequency  $f$ . The area  $A = 2\pi a^2$  is set equal to that of the high  $T_c$  superconducting film. From the diffusion equation, the temperature distribution in the substrate is

$$T = T_0 + \Delta T a r^{-1} e^{-(a-r)/L} e^{i(2\pi f t - r/L)}, \quad (2)$$

where  $L = (D/\pi f)^{1/2}$  is the thermal diffusion length on the time scale of the signal modulation,  $D = \kappa_S/c_S$  is the thermal diffusion constant, and  $c_S$  is the substrate heat capacity per unit volume. From Eqs.(1) and (2),

$$G_S(f) = A \kappa_S a^{-1} [(1+a/L)^2 + (a/L)^2]^{1/2}. \quad (3)$$

At low frequencies,  $L \gg a$ ,  $G_S(0) = A \kappa_S/a$ , which is equal to the thermal conductance of a cylinder with area  $A$  and length  $a$ . At high frequencies,  $L \ll a$ , and the heat can propagate only a very short distance  $L$ . The effective length of the cylinder is then  $L$ , giving a thermal conductance  $G_S(f) = A \kappa_S/L$ , which scales as  $f^{1/2}$ . This increase of the thermal conductance degrades the performance of the microbolometer at high frequencies. The frequency



$f_c = 2k_s/Ac_s$  at which  $L=a$  is listed in Table I for various substrates. Heat dissipated in the film can also be distributed to the substrate by conduction through the metal film antenna. Estimates of this conduction channel suggest that it can be significant compared with the conduction into the substrates with lower thermal conductivity in Table I. The numerical values depend on the details of the design. In principle, this conduction channel can be reduced by making the antenna from a superconductor with higher  $T_c$  than the one used for the thermometer.

In Table I we list the thermal and far-infrared properties of several commonly used substrates for high  $T_c$  superconducting films. The extinction lengths,<sup>11,14-17</sup> of all of the listed materials are long enough for operation at wavelengths down to 100  $\mu\text{m}$ . Because of its high dielectric constant,  $\text{SrTiO}_3$  is not listed. Fused and crystalline quartz would be very useful substrates for microbolometers because of their small dielectric constant and wide range of thermal conductances. However, they are not favorable substrates for the production of high quality films. The best candidates appear to be  $\text{MgO}$  for a fast microbolometer and  $\text{ZrO}_2$  stabilized with  $\text{Y}_2\text{O}_3$  for a slower, more sensitive bolometer. Anti-reflection coatings<sup>3</sup> may be required for high optical efficiency.

Following the derivation in Ref. 1, the voltage responsivity of a transition edge bolometer can be written as

$$|S|^2 = \left[ \frac{\alpha R_c}{G(f) \delta T} \right]. \quad (4)$$

In principle, response can also be observed due to heating of the quasiparticles above the phonon temperature<sup>18</sup> and the heating of the film above the temperature of the contiguous substrate. These effects are expected to be very fast, but to have very small responsivity. The numerical factor  $\alpha < 1$  is to insure thermal stability; we will choose  $\alpha = 0.3$ . In this expression the temperature coefficient  $d(\ln R)/dT$  at the bias point, which appears in conventional bolometer theory has been replaced by the inverse of the half-width  $\delta T$  of the superconducting transition.

The noise equivalent power (NEP) of the microbolometer can be computed by summing the squares of statistically independent contributions,

$$\text{NEP} = \frac{1}{\eta} \left[ 4k_B T_C^2 G(f) + \frac{4k_B T_C R_C}{|S|^2} + \frac{BV^2}{f|S|^2} + \frac{4k_B T_N R_C}{|S|^2} \right]^{1/2}, \quad (5)$$

where  $\eta$  is the optical efficiency. Values of  $\eta$  larger than 50% have been measured for log-periodic<sup>4</sup> and spiral<sup>5</sup> antennas on quartz. The first term in Eq. (5) arises from the thermal fluctuations, or phonon noise in the microbolometer. The second term is the Johnson noise in the resistance  $R_C$  of the high  $T_C$  superconducting film at the midpoint of the transition. The third term represents the  $1/f$  noise in the film, which we assume<sup>1</sup> to have a spectral density of the form  $S_V(f) = BV^2/f$ , where  $V$  is the bias voltage and  $B$  depends on the quality of the film. It is expected that  $B$  will increase with decreasing film volume. Because of the high speed of the microbolometer, however, operation may be possible at high enough frequencies that this term will not be important. The last term arises from an amplifier with noise temperature  $T_N$ .

It can be seen from Eqs.(4) and (5) that the ratio of the squares of the limits to the NEP from phonon noise and Johnson noise is

$$\left[ \frac{(\text{NEP})_{\text{phonon}}}{(\text{NEP})_{\text{Johnson}}} \right]^2 = (\alpha T_c / \delta T) . \quad (6)$$

With  $\alpha = 0.3$  and a conservative value of  $\delta T = 2$  K, this ratio is equal to 16.

Johnson noise in a  $10^2 \Omega$  resistor at 90 K is  $\sim 0.7 \text{ nVHz}^{-1/2}$ , which is comparable to the best amplifiers for frequencies  $f > 10^3$  Hz. If the  $1/f$  noise can be kept small by the use of high quality films, then the high  $T_c$  superconducting microbolometer will be strongly limited by phonon noise.

No noise term has been included in Eq.(5) to represent fluctuations in the rate of arrival of photons from the signal or from background sources. Because of the single mode throughput, estimates of the photon noise limit from a 300 K source at wavelengths  $\lambda > 100 \mu\text{m}$  give  $\text{NEP} \sim 10^{-15} \text{ WHz}^{-1/2}$ , which is too small to be important for the high  $T_c$  superconducting microbolometer.

In Fig. 2 we plot estimates of the NEP, including contributions from phonon and Johnson noise, for microbolometers with area  $A = 5 \mu\text{m}^2$  on various substrates as a function of the signal modulation frequency. The performance of a commercial room temperature pyroelectric detector<sup>19</sup> is also plotted for comparison. For a fused  $\text{SiO}_2$  substrate, values of  $\text{NEP} = 2.5 \times 10^{-12} \text{ WHz}^{-1/2}$  can be obtained at frequencies up to 10 kHz with a factor 2 increase by  $\sim 1$  MHz. For a high thermal conductivity substrate such as  $\text{Al}_2\text{O}_3$ , the NEP is slightly below  $10^{-10} \text{ WHz}^{-1/2}$  at low frequencies and increases by a factor 2 at  $\sim 10^9$  Hz, which corresponds to a pulse width  $\sim 1$  ns. Because of the absence of data on films of such small size,  $1/f$  noise has been neglected. We expect the  $1/f$  noise to contribute to the NEP at some low frequency.

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TABLE I. Thermal and far-infrared properties of several commonly used substrates for high  $T_c$  superconducting thin films.

Substrate materials	Thermal conductivity <sup>a</sup> $\kappa_S$ (W/cm K)	Specific Heat <sup>b,c</sup> $c_S$ (J/cm <sup>3</sup> K)	$f_c=2\kappa_S/Ac_S$ (Hz)	Thermal conductance <sup>d</sup> $G_S$ (W/K)	Dielectric constant <sup>e,f</sup> ( $\epsilon$ )	Film quality <sup>g</sup>
Sapphire	6.4	0.39	$6.6 \times 10^8$	$3.6 \times 10^{-3}$	9	Good to excellent
Magnesium Oxide	3.4	0.53	$2.6 \times 10^8$	$1.9 \times 10^{-3}$	10	Excellent
Fused Quartz	0.0062	0.59	$4.2 \times 10^5$	$3.5 \times 10^{-6}$	4	Need buffer layer
Crystalline Quartz	0.35	0.59	$2.4 \times 10^7$	$2.0 \times 10^{-4}$	4	Need buffer layer
Doped Zirconia	0.015	0.70	$8.6 \times 10^5$	$8.4 \times 10^{-6}$	12.5	Excellent

<sup>a</sup> Reference 8. <sup>b</sup> Reference 9. <sup>c</sup> Reference 10. <sup>d</sup> The thermal conductance is calculated from Eq.(3) at zero frequency, the area A of the microbolometer is assumed to be  $1 \times 5 \mu\text{m}^2$ .

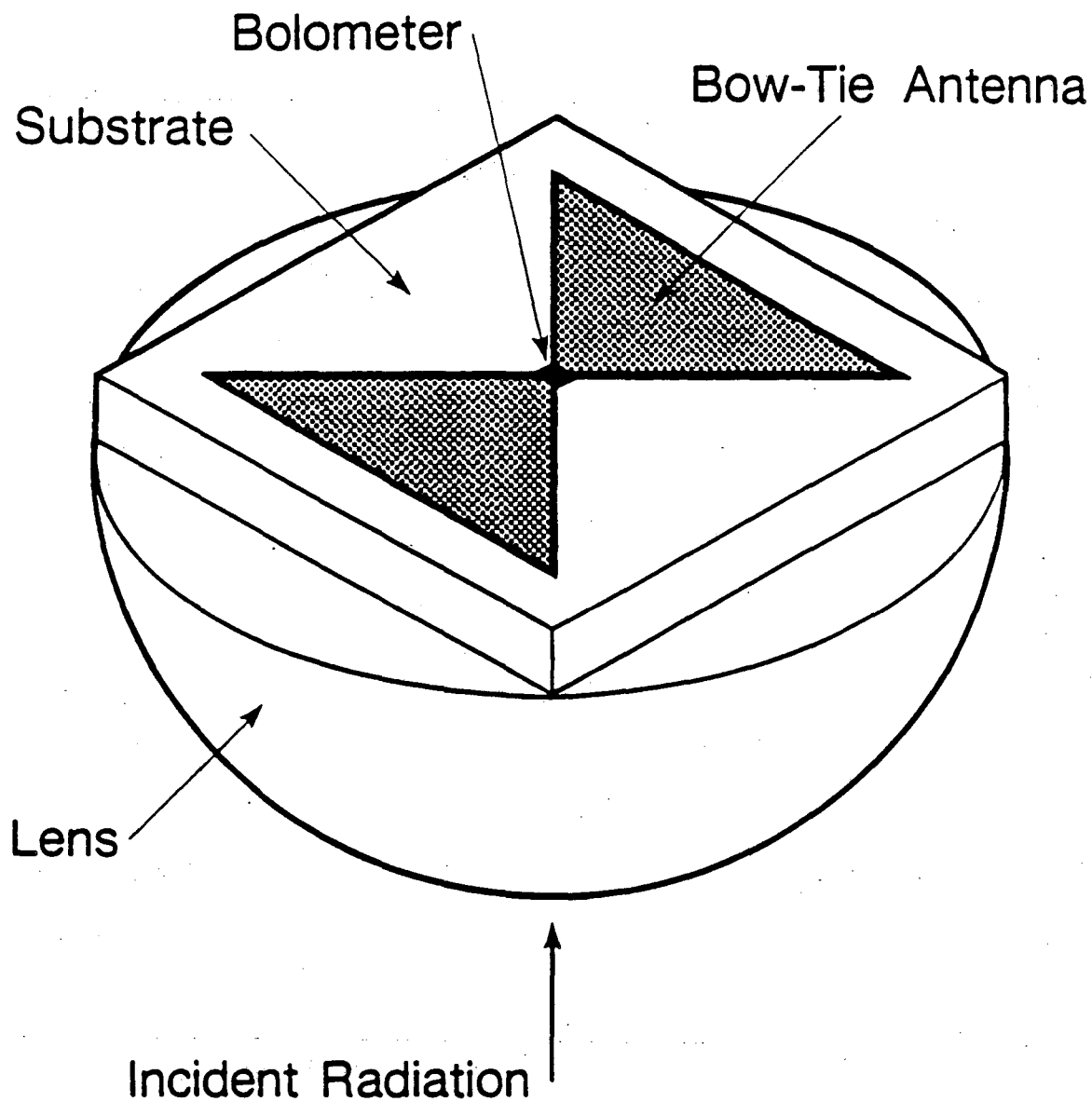
<sup>e</sup> Reference 11. <sup>f</sup> Reference 12. <sup>g</sup> Reference 13.

Figure Captions

Figure 1. Schematic of a 90° bow-tie antenna on the flat side of a hemispherical dielectric lens. Radiation is coupled to the antenna more efficiently through the lens and substrate.

Figure 2. (a)-(e) Computed values of the frequency dependent NEP of high  $T_C$  superconducting microbolometers on various substrates compared with that (f) of a commercial pyroelectric detector.<sup>19</sup> The substrates are (a) fused quartz, (b) yttria stabilized zirconia, (c) crystalline quartz, (d) magnesium oxide and (e) sapphire. The NEP's only include the contributions from the phonon and Johnson noise, that is,  $NEP = (NEP)_{\text{phonon}}(1+\delta T/\alpha T_C)^{1/2}$ . The values of  $G_S$  are listed in Table I. The numerical assumptions include an optical efficiency  $\eta = 0.5$ ,  $\alpha = 0.3$ , a film area of  $1 \times 5 \mu\text{m}^2$ ,  $T_C = 90 \text{ K}$ , and a transition width  $2 \delta T = 4 \text{ K}$ .





XBL 897-5127

FIGURE 1

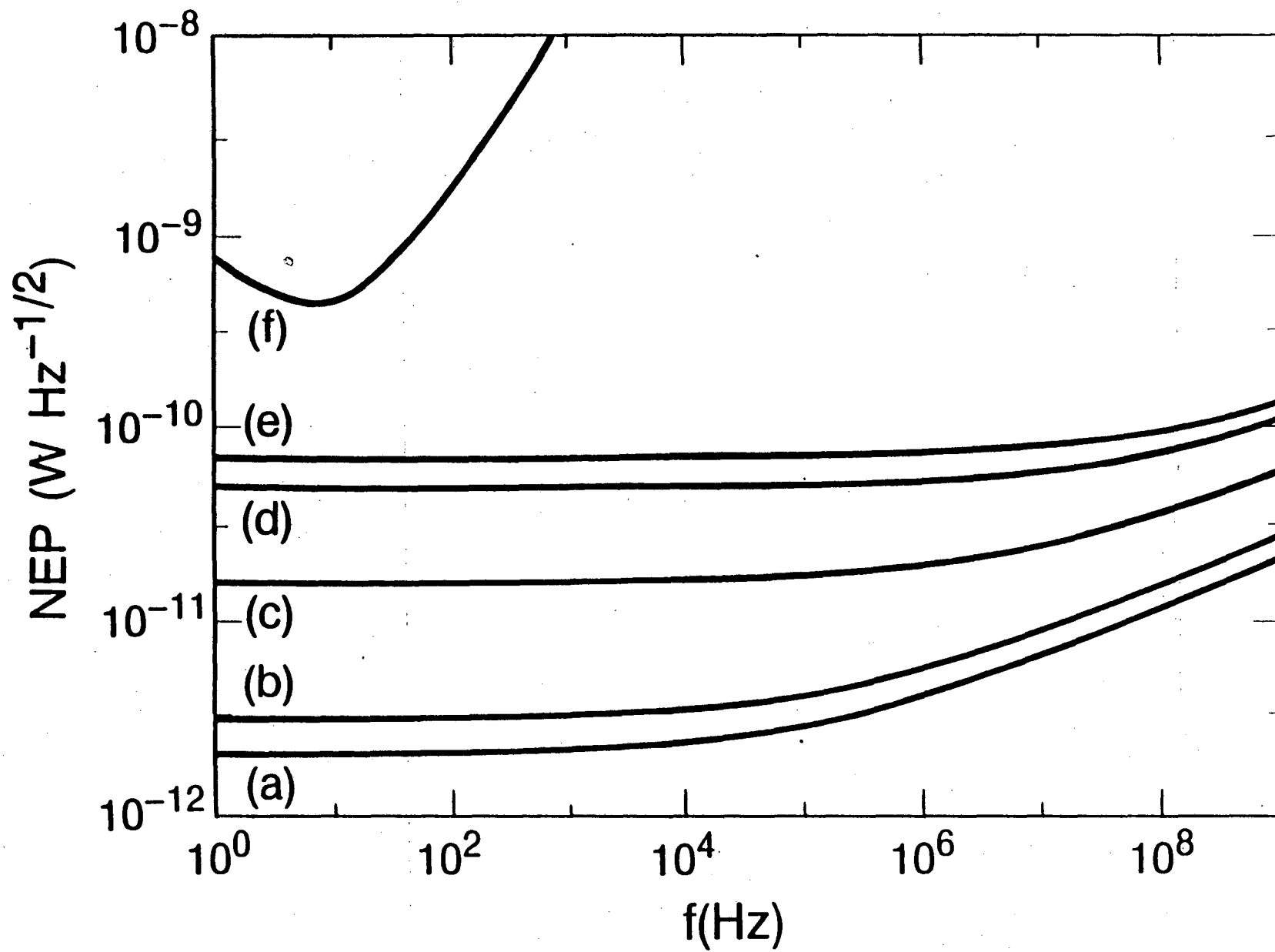


FIGURE 2

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