LBL-27645
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Materials & Chemical Sciences Division

Submitted to Applied Physics Letters

Design Analysis of a High T_c Superconducting Microbolometer

Qing Hu and P.L. Richards

August 1989

LOAN COPY
Circulates
for 2 weeks
Bldg. 50 Library.
LBL-27645
Copy 2

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-27645

DESIGN ANALYSIS OF A HIGH T_c SUPERCONDUCTING MICROBOLOMETER

Qing Hu* and P. L. Richards

Department of Physics, University of California,
and Materials and Chemical Sciences Division
Lawrence Berkeley Laboratory, Berkeley, California 94720

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 2.5×10^{-12} 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.

PACS numbers: 07.62. + s, 42.80. Sa, 44.10. + i, 74.75. + t, 85.60. Gz

* Present address: Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139.

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 μm.[1] 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 (≤25 μm) 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.[2] It has an NEP = 1.6×10^{-10} $WHz^{-1/2}$ up to several hundred kHz. We estimate that a 1×5 μm^2 YBCO microbolometer could have NEP = 2.5×10^{-12} $WHz^{-1/2}$ 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[2] 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.[3] The short wavelength limit of this technology is not well understood, but response has been demonstrated at 119 μm.[2] 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° bow tie. Others, with more useful antenna patterns include the log-periodic[4] and the spiral.[5] All are very broad band and have a frequency independent real antenna impedance[3] $R = 377[2(1+\varepsilon)]^{-1/2}\ \Omega$ that depends only on the dielectric constant ε 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 ~100 μΩcm just above T_c, the ratio of length to cross sectional area should be ~10^6 cm^{-1} to match a self-complementary antenna on a substrate with $\varepsilon = 10$. 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.[1] 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.[6] We have chosen a conservative film volume of $5 \times 1 \times 0.02$ μm^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[7] 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 termal conductance G_S from the high T_c superconducting film to the bulk of the substrate can be written as

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

where κ_S is the thermal conductivity of the substrate, T is the position dependent temperature in the substrate, ΔT 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

$$T = To + \Delta T a r^{-1} \, e^{(a-r)L} \, e^{i(2\pi ft - r/L)}, \tag{2}$$

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),

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

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

$f_c = 2\kappa_S/Ac_S$ 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,[11,14-17] of all of the listed materials are long enough for operation at wavelengths down to 100 μm. Because of its high dielectric constant, $SrTiO_3$ 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 MgO for a fast microbolometer and ZrO_2 stabilized with Y_2O_3 for a slower, more sensitive bolometer. Anti-reflection coatings[3] 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

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

In principle, response can also be observed due to heating of the quasiparticles above the phonon temperature[18] 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 δT of the superconducting transition.

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

$$\mathrm{NEP} = \frac{1}{\eta}\left[4k_B T_c^2 G(f) + \frac{4k_B T_c R_c}{|S|^2} + \frac{BV^2}{f|S|^2} + \frac{4k_B T_N R_c}{|S|^2}\right]^{1/2}, \tag{5}$$

where η is the optical efficiency. Values of η larger than 50% have been measured for log-periodic[4] and spiral[5] 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[1] 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

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

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 Ω resistor at 90 K is ~0.7 $nVHz^{-1/2}$, 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 throughout, estimates of the photon noise limit from a 300 K source at wavelengths $\lambda>100$ μm give NEP ~ 10^{-15} $WHz^{-1/2}$, 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 $A = 5$ μm^2 on various substrates as a function of the signal modulation frequency. The performance of a commercial room temperature pyroelectric detector[19] is also plotted for comparison. For a fused SiO_2 substrate, values of NEP = 2.5×10^{-12} $WHz^{-1/2}$ can be obtained at frequencies up to 10 kHz with a factor 2 increase by ~1 MHz. For a high thermal conductivity substrate such as Al_2O_3, the NEP is slightly below 10^{-10} $WHz^{-1/2}$ at low frequencies and increases by a factor 2 at ~10^9 Hz, which corresponds to a pulse width ~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.

We would like to thank S. Verghese, C.A. Mears, and S.R. Spielman for helpful conversations. This work was supported in part by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03-76-SF00098, and by the Department of Defense.

References

1. 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).

2. T.L. Hwang, S.E. Schwarz, and D.B. Rutledge, Appl. Phys. Lett. 34, 773 (1978).

3. D.B. Rutledge, D.P. Neikirk, and D.P. Kasilingam, in Infrared and Millimeter Waves, edited by K.J. Button (Academic Press, New York, 1983) pp. 1-90.

4. P.H. Siegel, IEEE Microwave Theory Tech. MTT-S Digest, 649 (1986).

5. P.P. Tong, Ph.D. thesis, California Institute of Technology, 1984, chapter 3, (unpublished).

6. S.E. Russek, D.J. Lathrop, B. Moeckly, and R.A. Buhrman, Bull. Am. Phys. Soc. 34, 890 (1989).

7. E.T. Swartz and R.O. Pohl, Appl. Phys. Lett. 51, 2200 (1987).

8. Thermophysical Properties of Inorganic Solids, vol. 2, edited by Y.S. Touloukian, 3rd. edition (Plenum Publishing Co., New York, 1978).

9. Thermophysical Properties of Inorganic Solids, vol. 5, edited by Y.S. Touloukian, 2nd. edition (Plenum Publishing Co., New York, 1980).

10. CRC Handbook of Chemistry and Physics, 3rd edition (Chemical Rubber Publishing Company, 1966).

11. M.N. Afsar, IEEE Trans. Microwave Theory Tech. MTT-32, 1598 (1984).

12. American Institute of Physics Handbook, 3rd edition (McGraw-Hill Co., New York, 1972), chapter 9.

13. M.R. Beasley, to be published in a special issue of IEEE Proceedings on Superconductors and Their Applications, October 1989 and references therein.

14. E.V. Lowenstein, D.R. Smith, and R.L. Morgan, Appl. Opt. 12, 398 (1973).

15. C.M. Randall and R.D. Rawcliffe, Appl. Opt. 6, 1889 (1967).

16. P. Meyer and D. Petitgrand, Revue de Physique Appliquée 11, 23 (1976).

17. W. Creager, private communications on the far-infrared transmission properties of zirconia, 1989.

18. E.M. Gershenzon, M.E. Gershenzon, G.N. Gol'tsman, A.D. Semenov, B.S. Karasik, and A.V. Sergeev, JETP Lett. 46, 285 (1987).

19. Model P-41 pyroelectric detector, Molectron Corp., Sunnyvale, California.

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

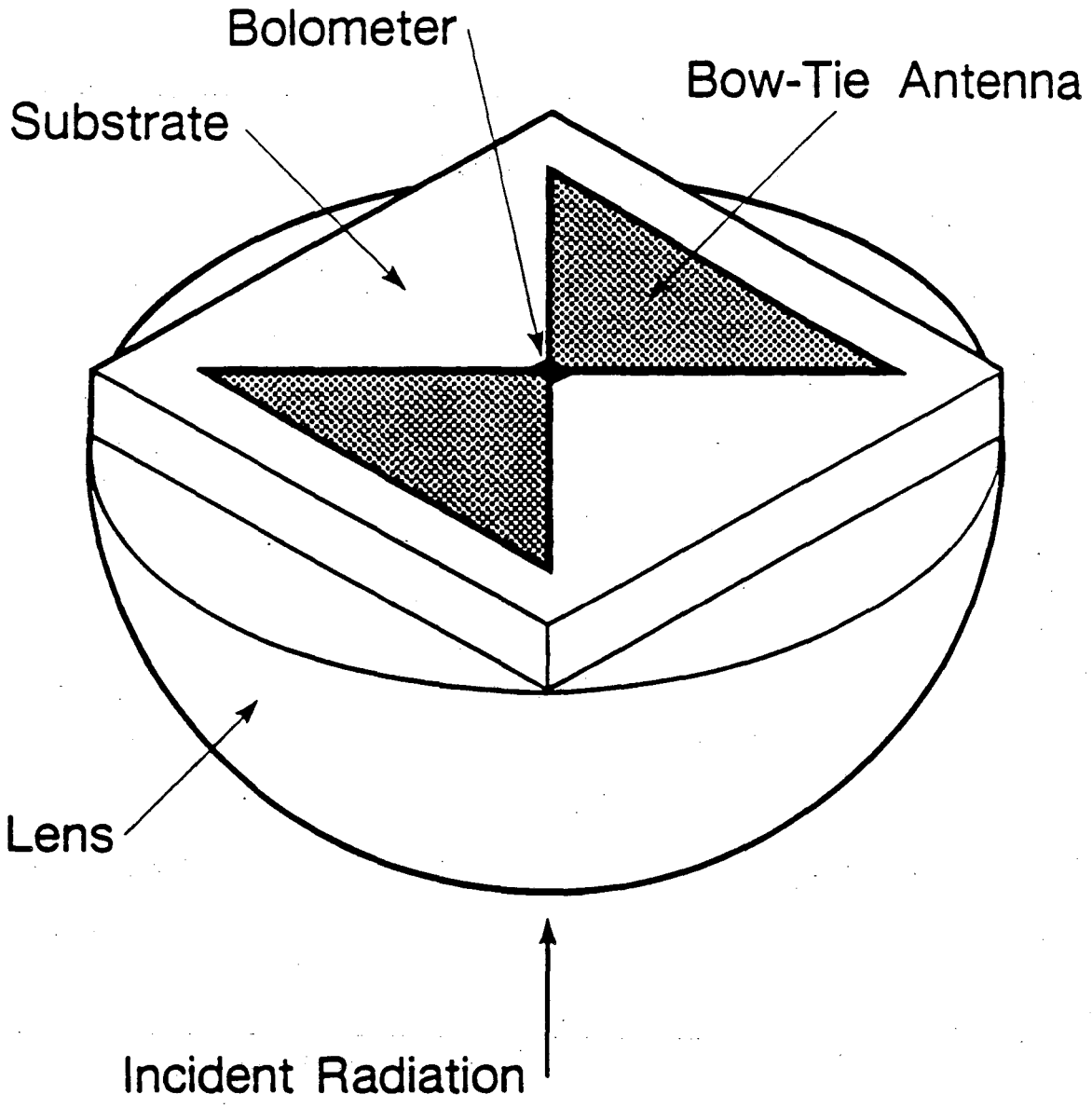
Substrate materials	Thermal conductivity[a] κ_S (W/cm K)	Specific Heat[b,c] c_S(J/cm^{3}K)	$f_c = 2\kappa_S/Ac_S$ (Hz)	Thermal conductance[d] G_S(W/K)	Dielectric constant[e,f] (ε)	Film quality[g]
Sapphire	6.4	0.39	6.6×10^8	3.6×10^{-3}	9	Good to excellent
Magnesium Oxide	3.4	0.53	2.6×10^8	1.9×10^{-3}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

[a] Reference 8. [b] Reference 9. [c] Reference 10. [d] The thermal conductance is calculated from Eq.(3) at zero frequency, the area A of the microbolometer is assumed to be 1×5 μm^2.
[e] Reference 11. [f] Reference 12. [g] Reference 13.

Figure Captions

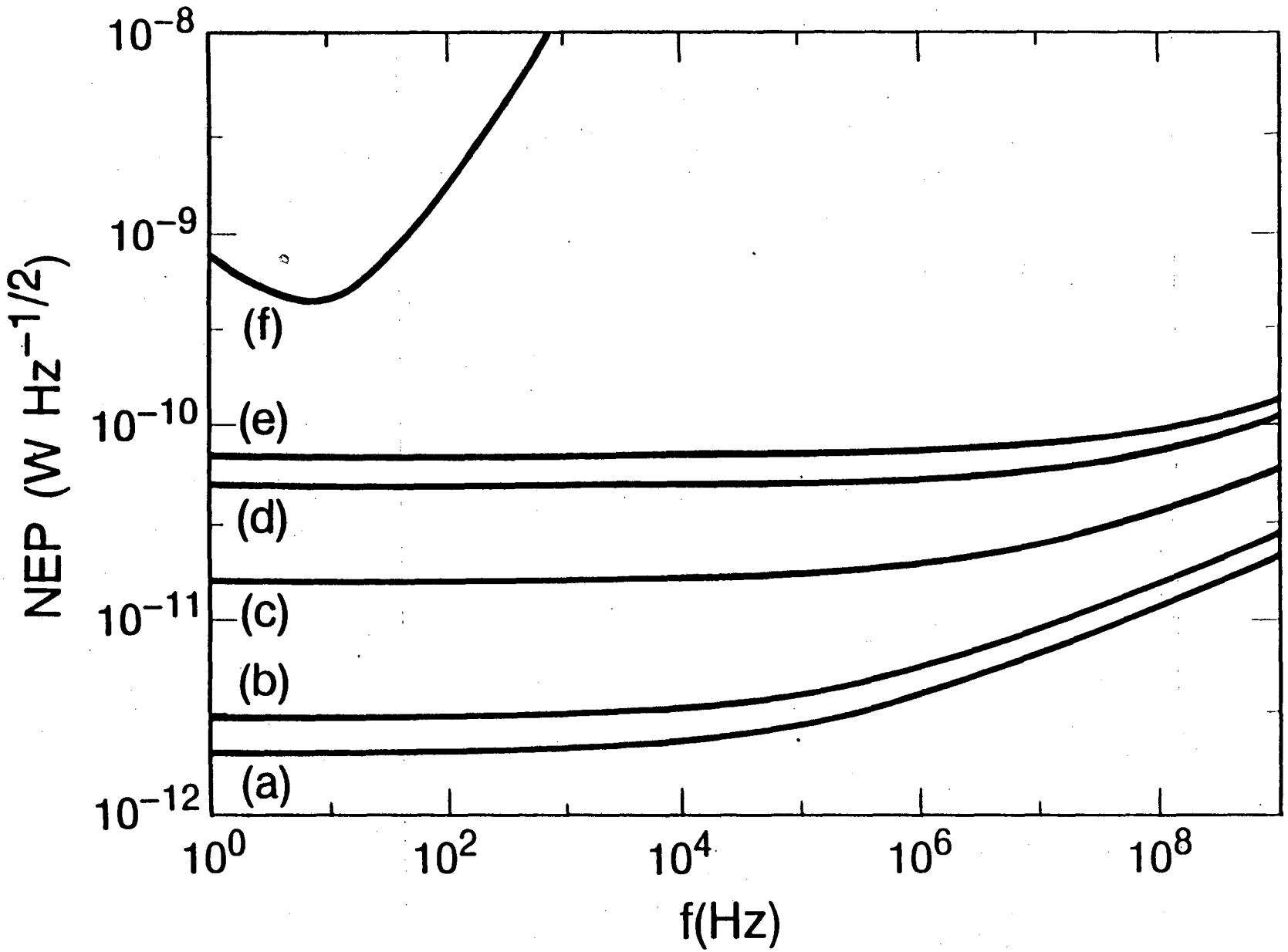
Figure 1. Schematic of a 90° bow-tie antenna on the flat side of a hemispherical dielectric lens. Radiation is coupled to the antenna more efficiently through the lens and substrate.

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.[19] 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, $NEP = (NEP)_{phonon}(1+\delta T/\alpha T_c)^{1/2}$. 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 $1\times5\ \mu m^2$, $T_c = 90$ K, and a transition width $2\ \delta T = 4$ K.



XBL 897-5127

FIGURE 1



XBL 897-5126

FIGURE 2

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720