A Hot-Electron Direct Detector for Radioastronomy

Boris S. Karasik

Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, CA 91109, USA

Acknowledgment

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under the contract with the National Aeronautics and Space Administration

Layout

- Radioastronomy needs
- Operation principle
- Materials (electron-phonon interaction)
- Sizes
- Performance
- Summary

Submillimeter radioastronomy needs

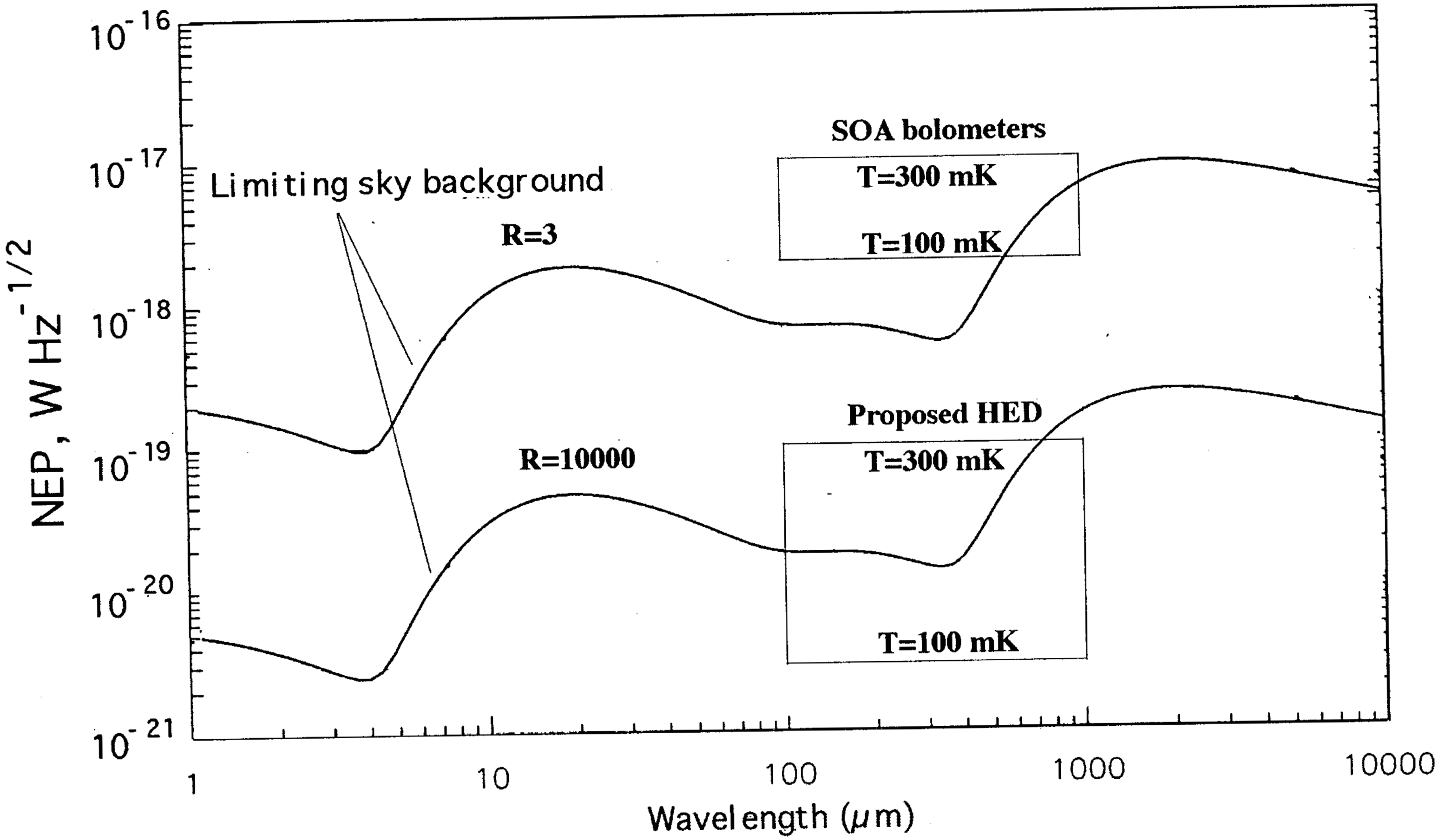
- Studies of the early universe
  - -formation of stars and galaxies;
  - -evolution of galaxies and structures;
  - -history of energy release, nucleosynthesis, and dust formation.
- Anisotropy of the Microwave Background Radiation

Requirements for future radioastronomy SMM detectors

Future infrared and submillimeter radioastronomy missions (Next Generation Space Telescope, Submillimeter Probe of the Evolution of Cosmic Structure) require better detector technology:

State-of-the-art (SOA)	Needed
NEP$\approx 10^{-18}$-10^{-17} W Hz$^{-1/2}$	• 10^{-20}-10^{-19} W Hz$^{-1/2}$
	• high spectral resolution (10^{3}-10^{4})
	• cold optics (~4 K)
Time constant $\approx$0.1-1 ms	• 0.01-0.1 msec and less (adjustable)
	• fast sky mapping
	• fast bolometer array multiplexing
	• low fabrication cost

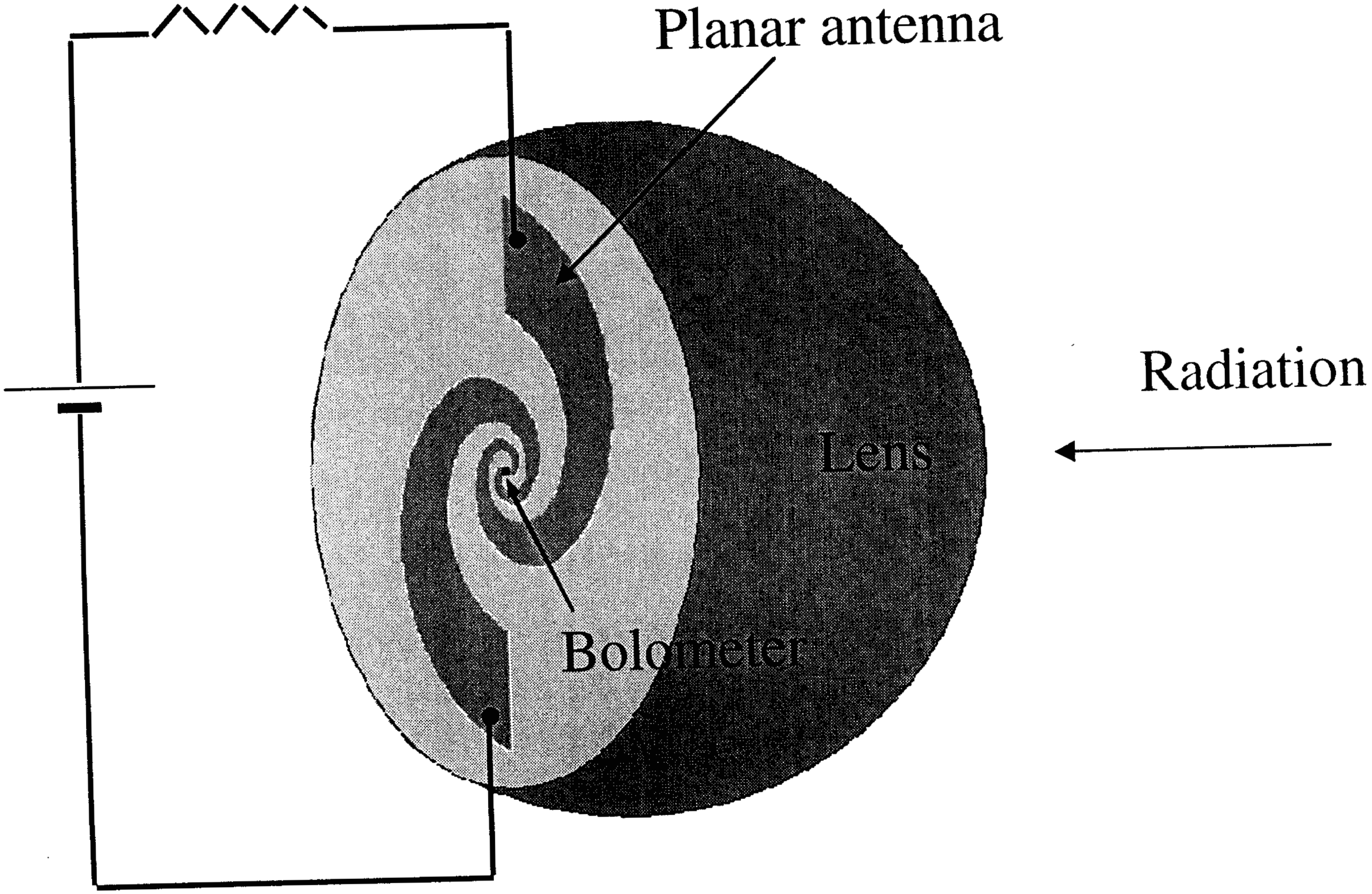
The sensitivity of the ideal photon noise limited detector



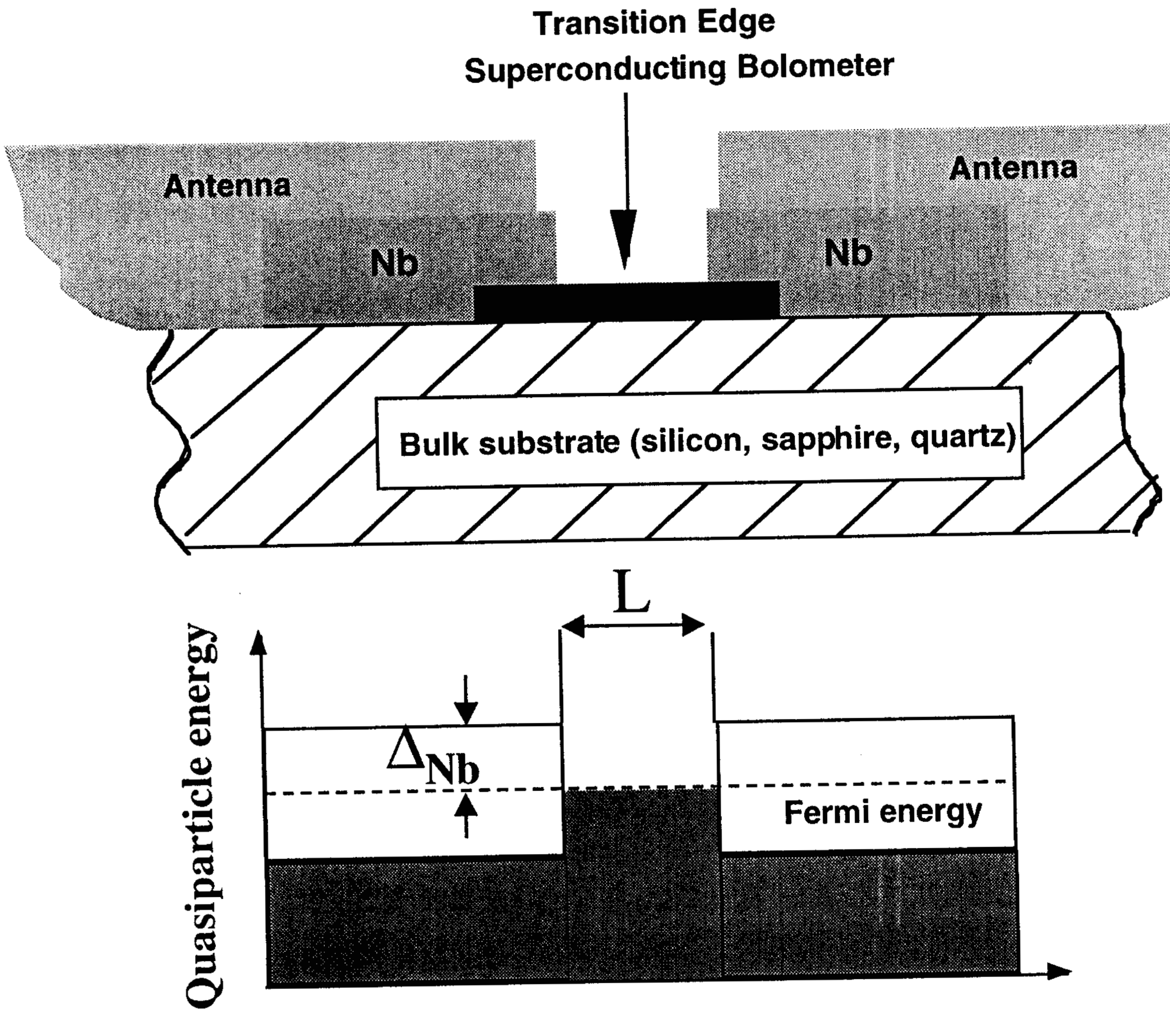
Hot-electron bolometer detector

- The bolometer speed is determined by the electron-phonon relaxation time, $\tau_{e\text{-}ph}$.
- NEP = $(4k_BT^2C_e/\tau_{e\text{-}ph})^{1/2}$ can be very small for a submicron size device.
- $\tau_{e\text{-}ph}$ depends on the mean free path of electrons ($\tau_{e\text{-}ph} \sim D^{-1}$). It can be "adjusted" to a convenient value of 0.1-1.0 msec. This will result in a very low NEP of 10^{-21}-10^{-20} WHz$^{-1/2}$ (depending on the material).
- The superconducting bolometer can be voltage biased and, therefore, its speed can be additionally increased due to the negative electro-thermal feedback (ETF) without loosing the sensitivity.

Antenna-coupled bolometer



Andreev reflection in HED



Boris Karasik, 2nd Int.Workshop on HEB, 9/3/1999

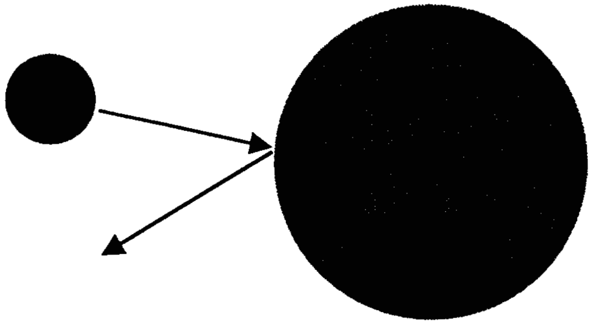
Materials

- Low-T_c superconducting metals (W, Hf, Ti)
- Normal-superconducting bi-layers (Mo/Au, Al/Ag, Al/Cu)
- Low $C_e = \gamma T$ is desirable

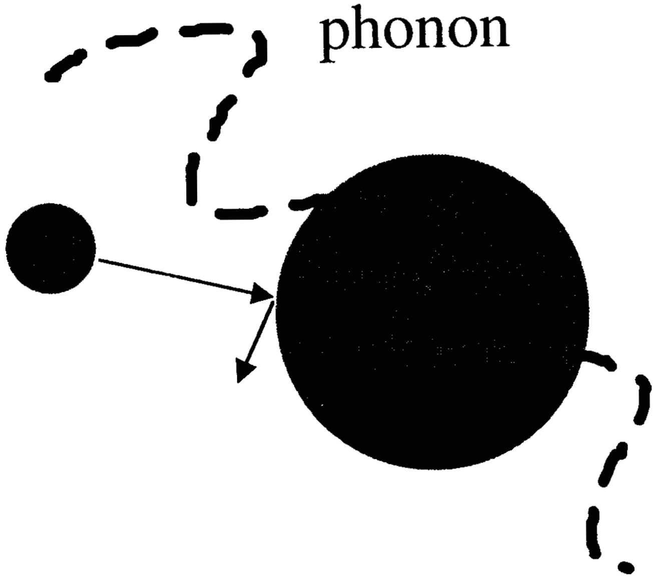
Electron-phonon scattering in dirty metal

- In a “pure” metal $\tau_0 \sim T^{-3}$
- Inelastic scattering by vibrating impurities
- Inelastic scattering by phonons
- Interference of scattering processes
- In a “dirty” metal at low temperatures **(ql<<1)**
  $\tau_{e\text{-}p} = \tau_0 * (ql)^{-1} \sim T^{-4} l^{-1} \sim D^{-1}$
- The electron mean free path can be controlled either by making film thinner or by ion irradiation

Scattering by vibrating impurities

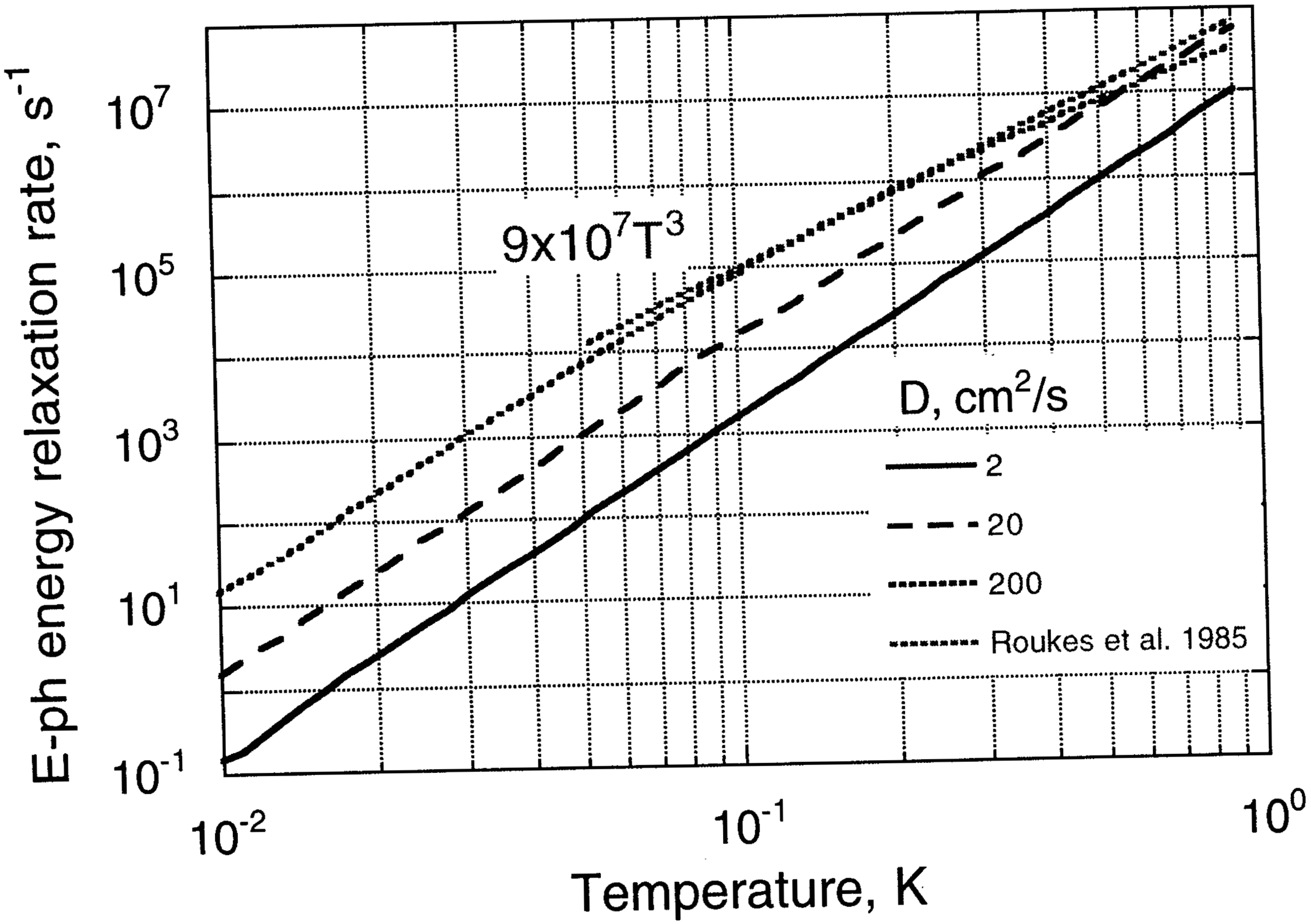


Steady impurity - elastic



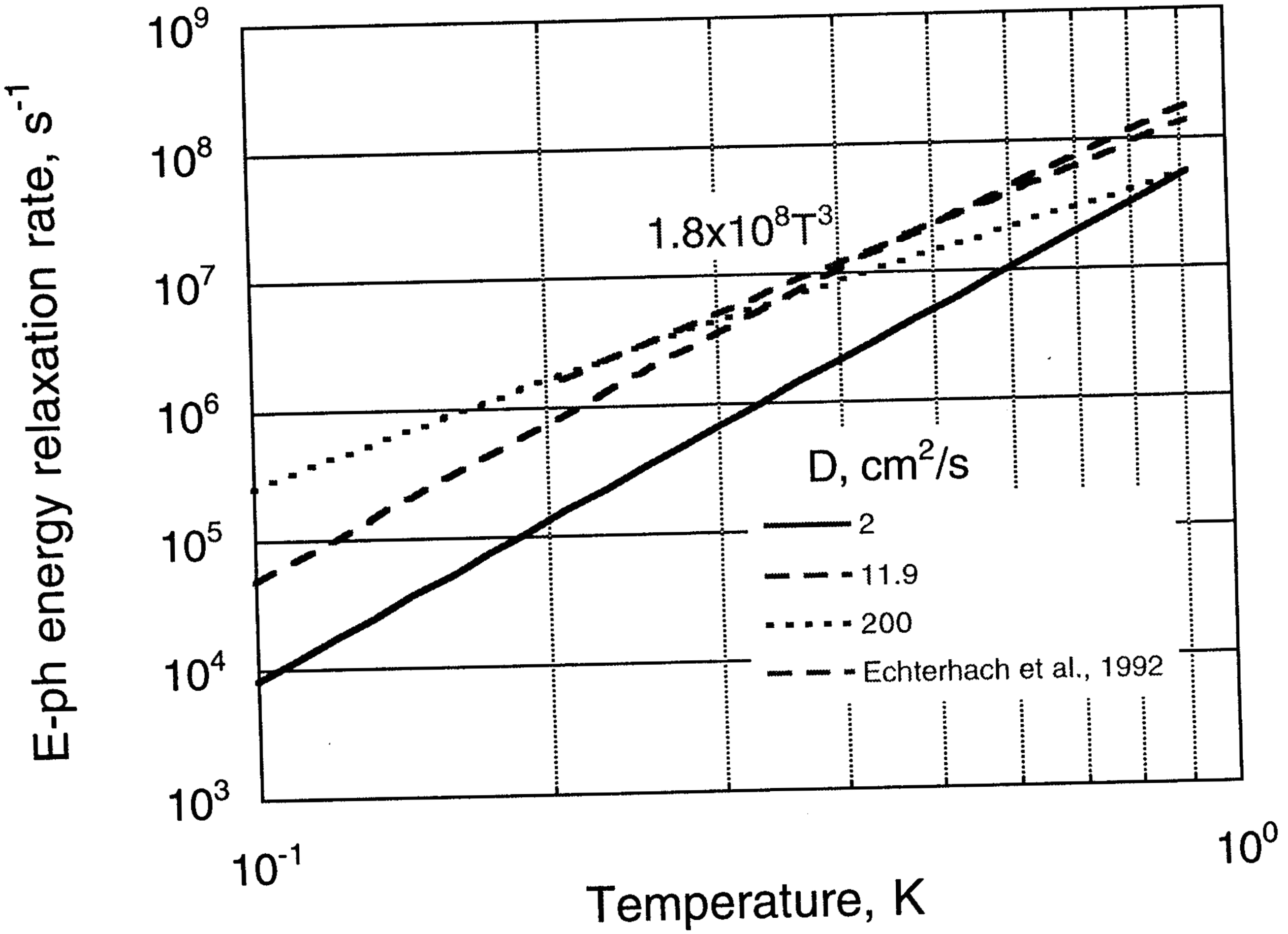
Vibrating impurity - inelastic

Cu



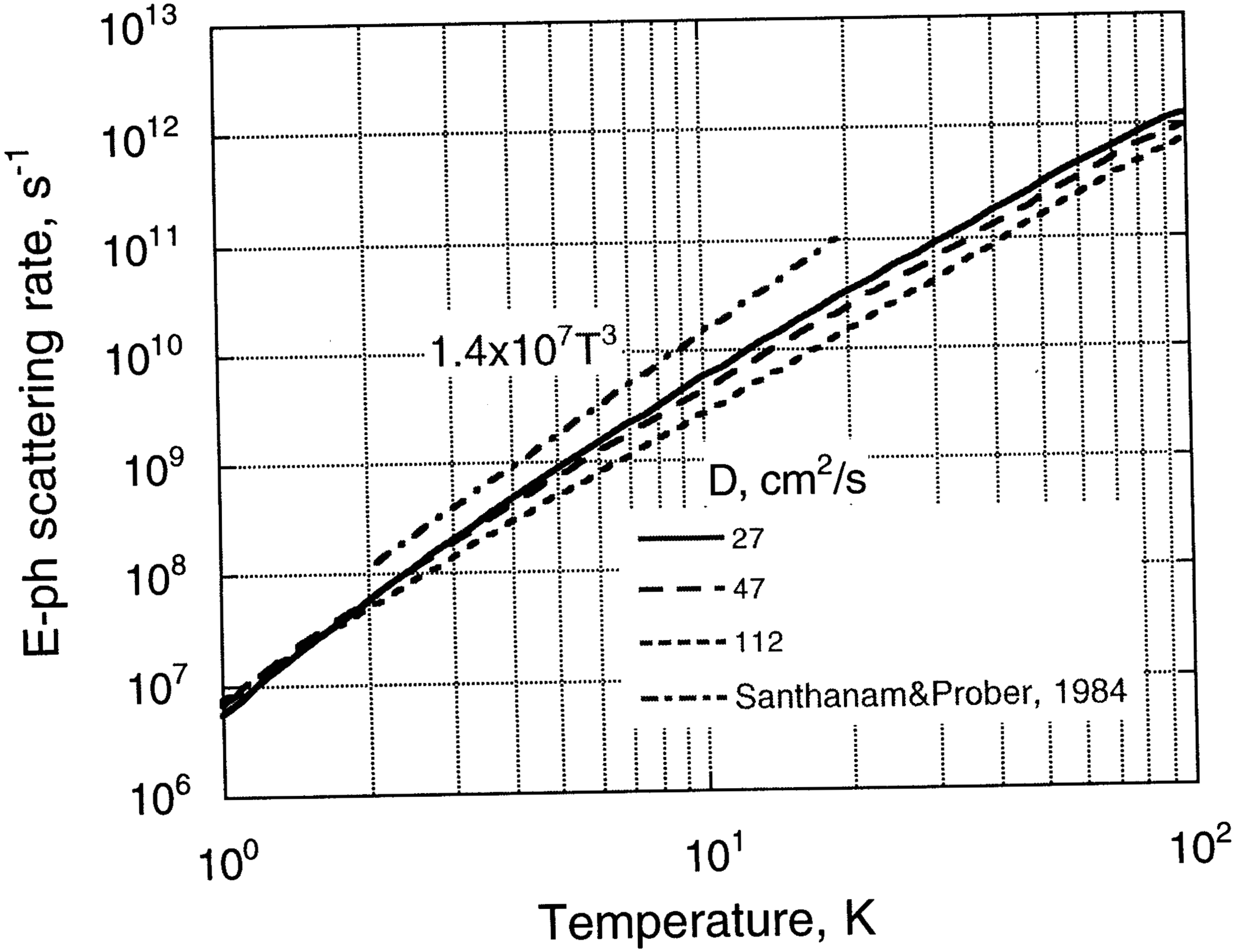
E-ph energy relaxation rate, s^{-1}
10^{7}
10^{5}
10^{3}
10^{1}
10^{-1}
10^{-2}
10^{-1}
10^{0}
Temperature, K
$9\times10^{7}T^{3}$
D, cm^2/s
2
20
200
Roukes et al. 1985

Au



E-ph energy relaxation rate, s^{-1}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^{-1}
10^0
Temperature, K
1.8x10^{8}T^3
D, cm^2/s
2
11.9
200
Echterhach et al., 1992

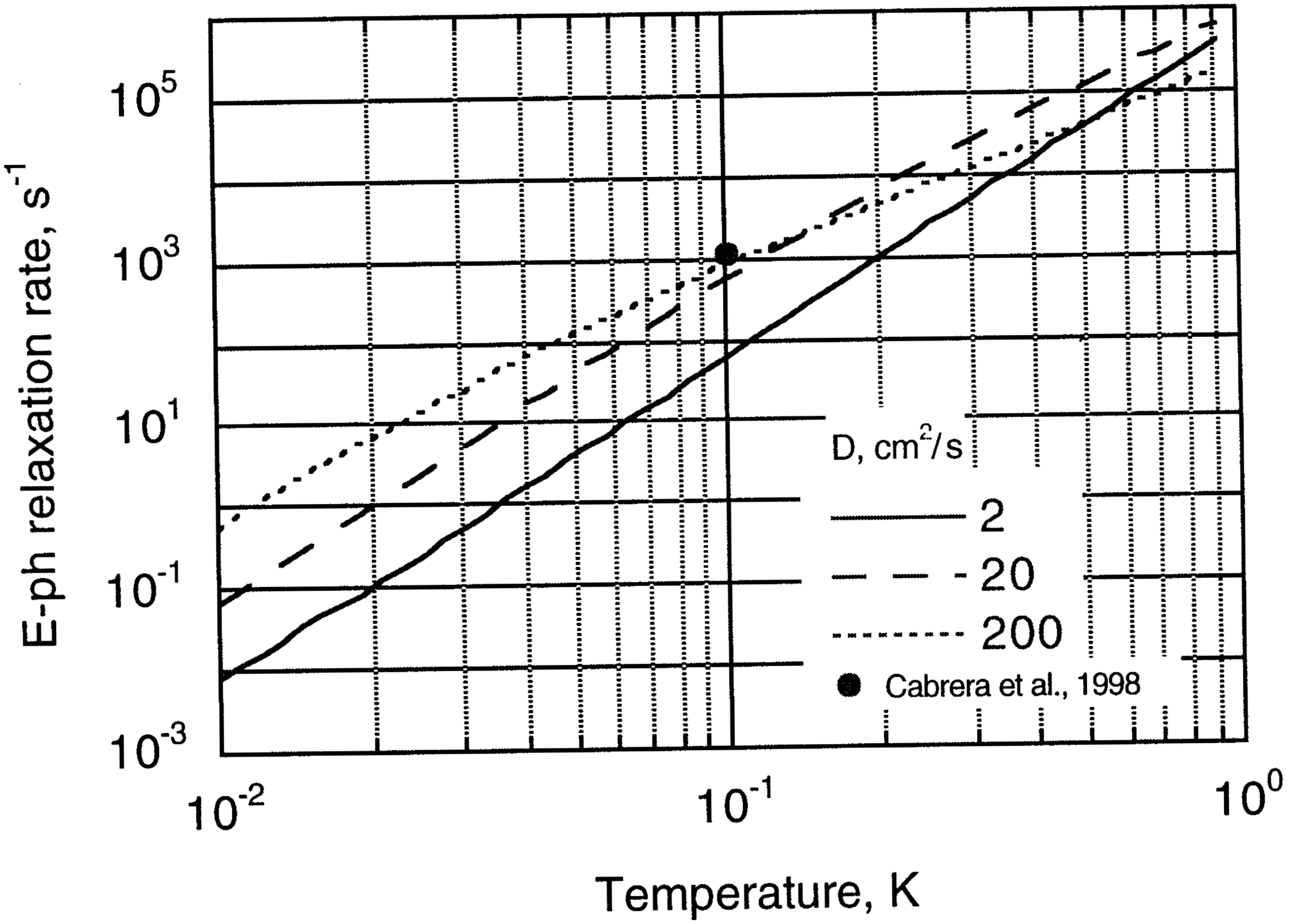
Al



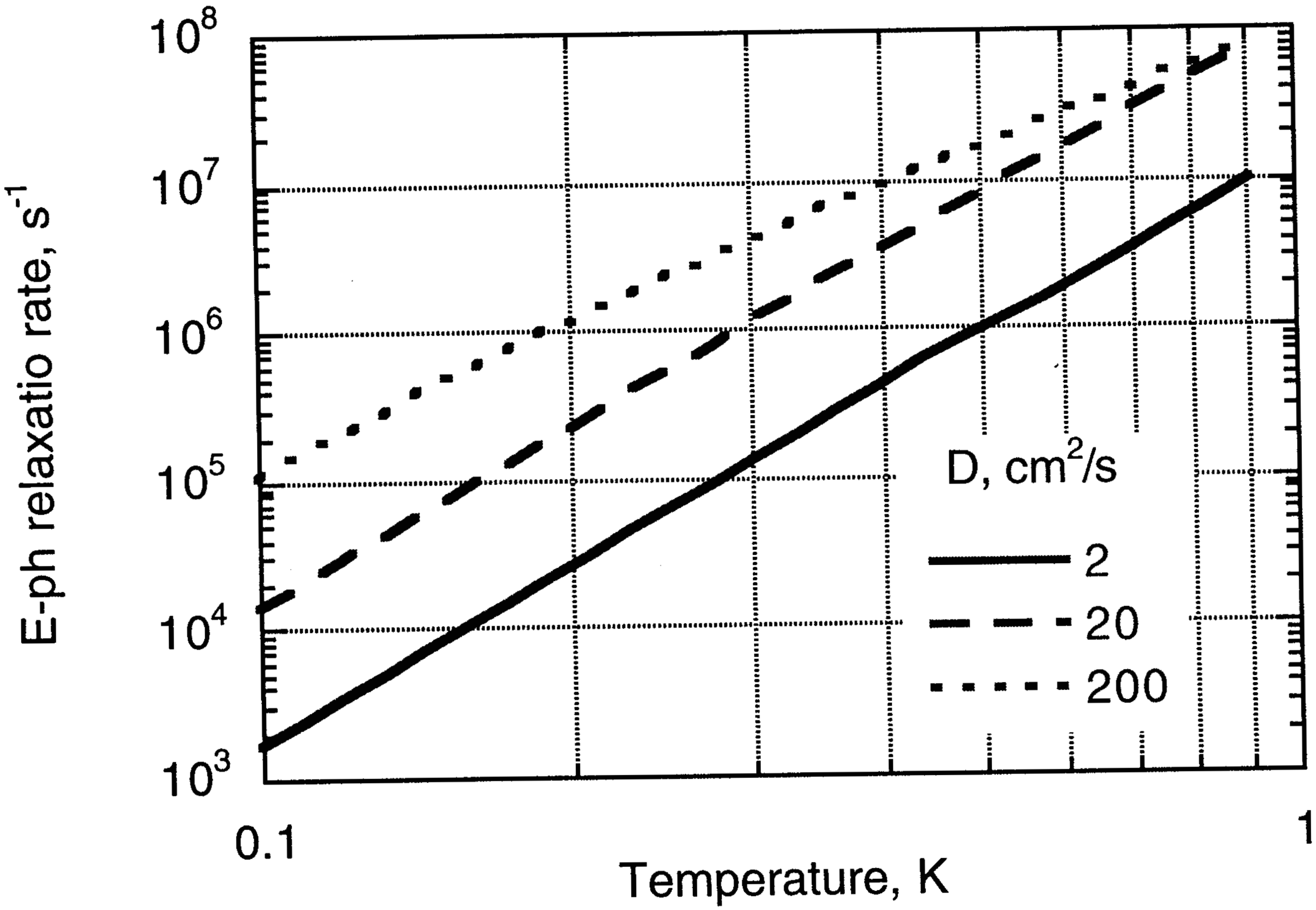
E-ph scattering rate, s^{-1}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
$1.4x10^7T^3$
D, cm^2/s
27
47
112
Santhanam&Prober, 1984
10^0
10^1
10^2
Temperature, K

W ($T_c \approx 0.1$ K)

JPL



Ti ($T_c \approx 0.3$ K)

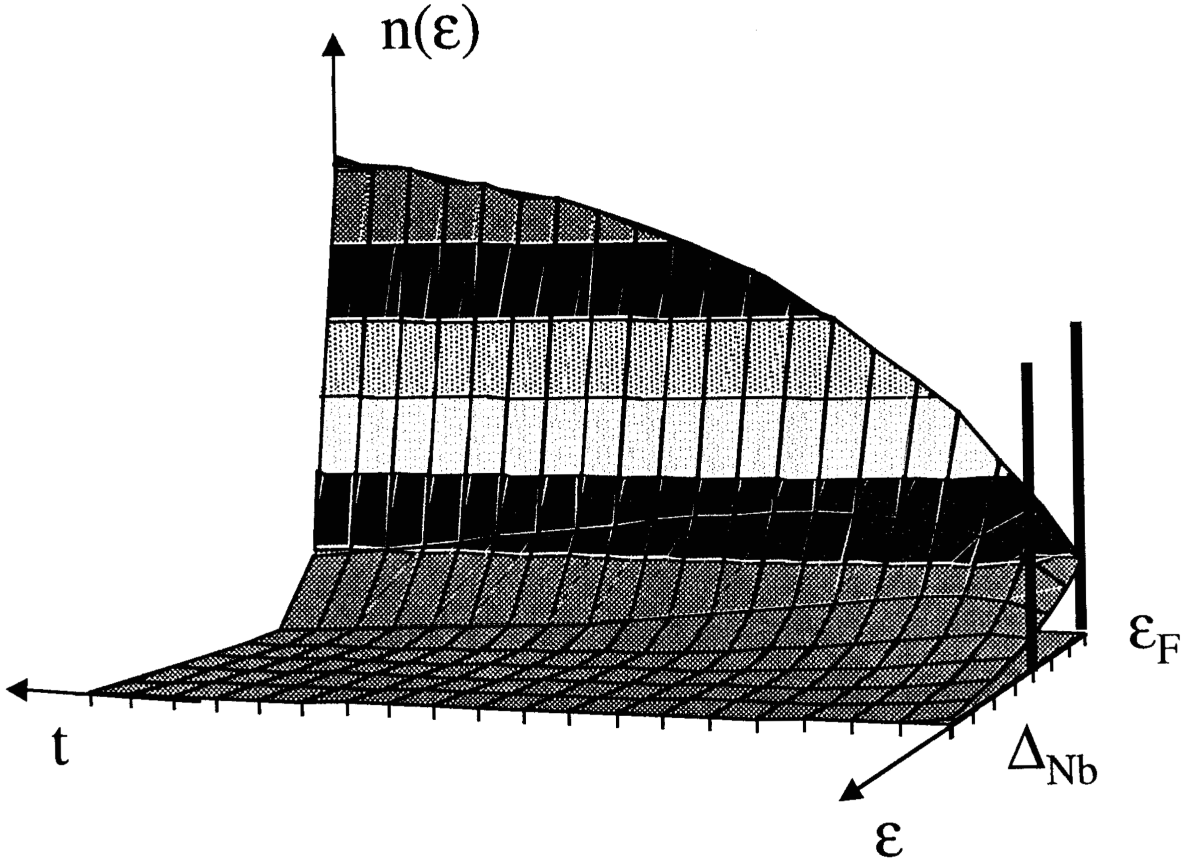


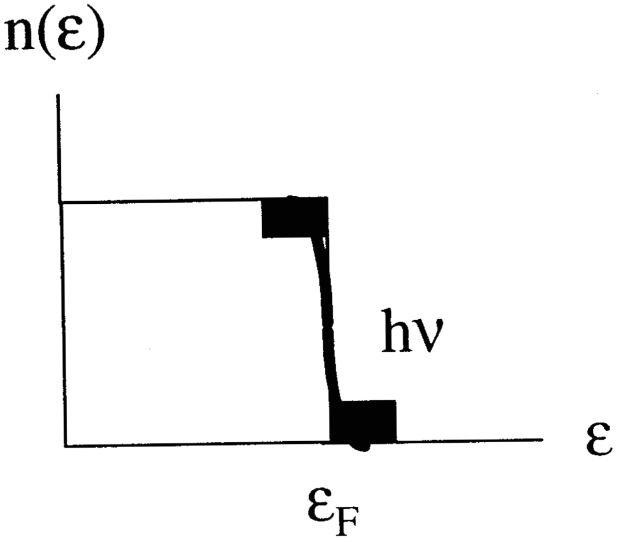
Sizes

The smaller the better (NEP ~ $\sqrt{\text{Volume}}$)

Length limits

A. Thermalization of qp with $\varepsilon>\Delta_{Nb}$



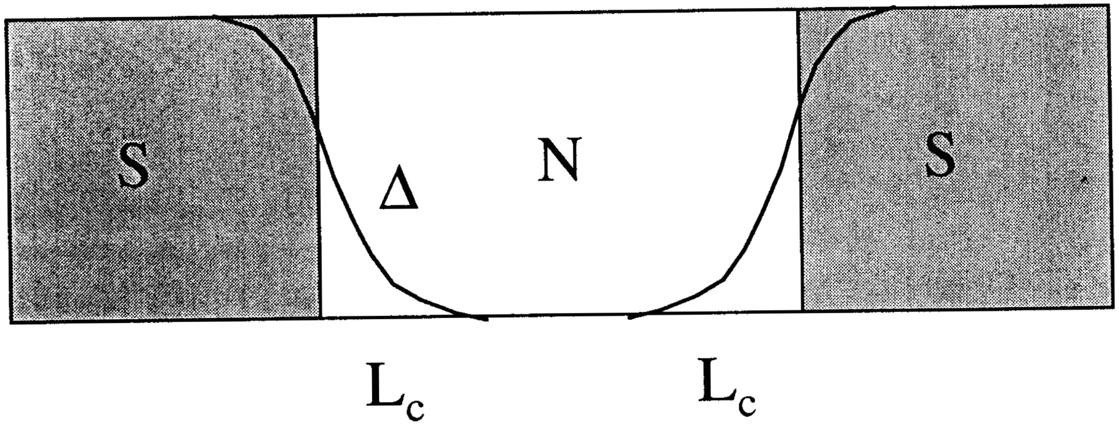


$L>[D\tau_{ee}(\Delta_{Nb})]^{1/2}\approx 90$ nm

$D\approx 2\ \mathrm{cm^2/s}$

Length limits (cont.)

B. Proximity effect



Coherence length in a normal metal

$L > 2L_c = 2(hD/4\pi^2 k_B T)^{1/2} \approx 100$ nm

Thickness limits

- The thinner film the more defects (τ_{ee} decreases, $\tau_{e\text{-}ph}$ increases)
- The sheet resistance increases when the thickness decreases ($R_s \approx 50\ \Omega$ is needed for the rf match to an antenna)
- NEP ~ $d^{1/2}$
- 5 nm < d < 10 nm is the optimal range

Expected performance of HED

Bolometer size 0.5×0.25×0.01 μm^3

Material	**τ, ms**	**NEP, W/$\sqrt{\text{Hz}}$**	**NEP$\sqrt{\tau}$, 10^{-22} W/$\sqrt{\text{Hz}}$**
W	**15**	**0.8×10^{-21}**	**1.0**
Ti	**0.007**	**2.9×10^{-19}**	**8.0**
Al	**0.02**	**1.1×10^{-19}**	**5.0**
Cu	**0.008**	**1.5×10^{-19}**	**4.0**

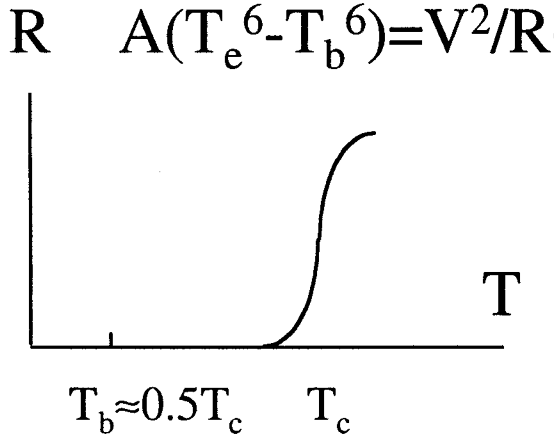
0.3 K

Better than the SOA detectors at 0.1 K!

Modeling of the HED performance

Tungsten HED

$A(T_e^6-T_b^6)=V^2/R(T_e)$



T_c=100 mK
δT_c=1 mK
R_n=100 Ω

Max neg. ETF effect
$L \approx 64$
$S_I \approx 3.5\times10^9$ A/W
$R \approx 0.3$ Ω

SQUID amp. contribution

$i_n \approx 1$ pA/√Hz NEP$_{\text{amp.}} \approx$ **3 ×10^{-22}** W/√Hz << NEP$_{\text{HED}}$

Johnson noise contribution

$\text{NEP}_J = (4k_BT_eP_{\text{Joule}})^{1/2}/L \approx$ **2 ×10^{-23}** W/√Hz << NEP$_{\text{HED}}$

Quantum shot noise should be suppressed by the ETF?

Conclusion

- An antenna-coupled HED can be used between 100 GHz and 30 THz
- It will be potentially more sensitive than any other existing type of the submillimeter detectors
- It is much faster than conventional bolometers
- It can be used either at lower temperature (100 mK) with superior sensitivity or at higher temperature (300 mK) with still high sensitivity and very high speed
- It can be easily integrated into either a quasioptical front-end unit (planar antenna+elliptical lens) or a waveguide chamber depending on the wavelength range
- It is simpler to fabricate: does not require fragile membrane or micromachined suspensions
- Much smaller bolometer size allows for larger packaging density