# I-2. QUANTITATIVE COMPARISON OF SOLID-STATE MICROWAVE DETECTORS

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Six classes of solid-state microwave detectors are compared in this paper. The primary criteria for comparison are sensitivity, frequency response, and dynamic range. Other performance criteria which are less easily characterized by a single numerical quantity, are also considered; examples of these are burnout and ease of impedance match.

Each class has distinguishing features which can be summarized briefly as follows:

Thermo-Electric Detectors have no rectifying barrier but depend upon localized distrubance of thermal equilibrium in the semiconductor to produce detection.[1] Since there is no barrier capacitance effect, the cutoff frequency is determined either by dielectric relaxation or by the characteristic time for thermalization of "hot" carriers. Hence, although their sensitivity may be lower than that of other devices, thermo-electric detectors offer the advantage of flat response at millimeter wavelengths. Fabrication by either a point-contact or a planar evaporated-contact process is relatively simple; planar process allows precise control of the dynamic (video) resistance over a wide range of values, and produces a device with high burnout capability.

Space Charge Limited Resistors are the solid-state equivalent of space charge limited thermionic diodes, but due to the proportionality of electron velocity rather than electron acceleration to electric field, the current varies as the square rather than the three-halves power of applied voltage.[2] Their distinguishing feature is an extremely broad square-law range of detection. There is no rectifying barrier in the space charge limited resistor, and recent analyses predict that these devices have potential usefulness as detectors in the microwave frequency range.[3]

Hot Carrier Diodes are metal-semiconductor Schottky barrier devices. When made with evaporated contacts they have a high degree of uniformity, moderate burnout tolerance, and are distinguished by an extremely low flicker noise coefficient which permits the use of bias current to facilitate impedance matching without a severe noise penalty.[4] Having a broad range of exponential ideality,they can be precisely analyzed.

Tunnel Diodes, when biased near the peak current, provide a better threshold sensitivity than any other device despite the low dynamic resistance and correspondingly high noise current.[5] High sensitivity results from the high conversion efficiency produced by the sharp non-linearity of the device; the non linearity also contains higher-order terms and this limits the dynamic range of square-law detection.

Backward Diodes are distinguished by their excellent thermal stability, since their characteristics result from quantum mechanical tunneling. They do not have the usual high peak current of a tunnel diode and do not require bias. The sensitivity of the device is somewhat lower than that of tunnel diodes, but the higher dynamic resistance simplifies impedance matching.[6,7]

Point Contact Diodes have extremely low barrier capacitance resulting from a structure which is also fragile and extremely susceptible to burnout. When forward biased, the point contact diode has more flicker noise than other devices, but the high barrier cutoff frequency offsets this effect for some applications.[8]

Threshold Sensitivity. In many detector applications, the primary consideration is threshold sensitivity.[9,10,11] To describe and specify threshold performance, various definitions have been used, but with respect to the new devices and improvements on old devices, these definitions are sometimes inadequate because the specified video bandwidths often do not coincide with the video bandwidths of contemplated applications. Since the video noise that is generated by the detector is frequency dependent, extrapolation of such data is tenuous. To establish an equivalent basis for comparison of devices alone, that is, without associated amplification circuitry, the term Noise Equivalent Power (NEP) is used. NEP has had long use in the field of light detection and measurement; it is defined as the input signal power required to produce unity signal/noise ratio (S/N) in a one-cycle-per-second (one Hertz) video bandwidth; NEP has the units "watts per root Hertz".

An expression has been developed for analyzing the threshold performance of a barrier-type microwave detector such as the point-contact or hot carrier diode. It combines the concept of NEP, the known noise properties of the device (specifically, "noise corner"), and the fact that the barrier-type device exhibits a cutoff frequency due to barrier capacitance and parasitic series resistance.

For a detector matched to the power source this expression can be written

$$\log\left(1 + f_{rf}^2/f_c^2\right) + 0.5\log\left(1 + f_N/f_V\right) = \log\left(NEP/NEP_O\right) \quad (1)$$

$f_{rf}$ is the rf (microwave) signal frequency

$f_c$ is the barrier cutoff frequency

$f_N$ is the noise corner (below which 1/f noise dominates)

$f_V$ is the video frequency

$NEP_O$ is the minimum possible value of NEP

The expression can be used to generate controus of equal sensitivity on coordinates of input frequency and output (video) frequency, as shown in Figure 1. Intersections of these contours for one device with equal NEP contours for another device describe a line in the RF-video spectrum plane which defines the region of preference with respect to threshold sensitivity, as shown in Figure 2. This system of contours can also yield an estimate of the threshold sensitivity of a device at any RF or

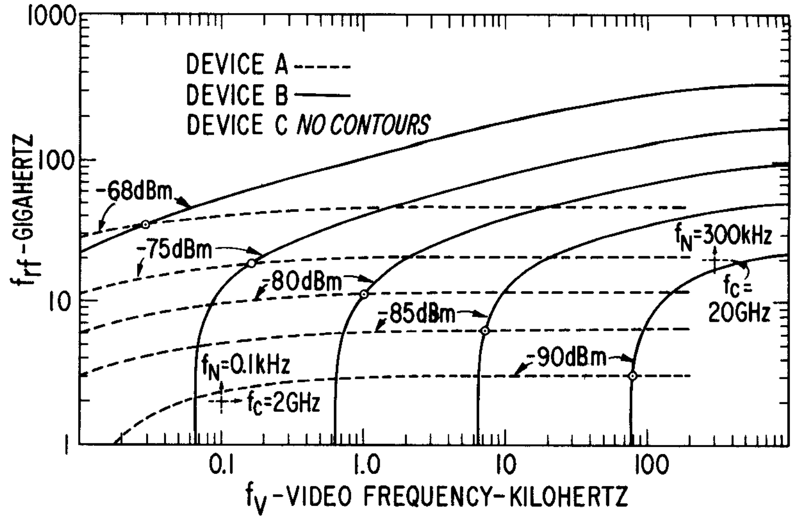


Figure 1. Noise Equivalent Power (NEP) Contours

for devices having the following properties at $R_V$=500Ω

| | | DEVICE | | |
|---|---|---|---|---|
| Property | Description | A | B | C |
| $NEP_o$ | NEP evaluated at Low RF, High Video frequencies (dBm) | -95 | -94 | -68 |
| $f_N$ | Noise corner; frequency at which flicker noise equals shot noise (kHz) | 0.1 | 300 | ≈0 |
| $f_c$ | Barrier RF cutoff frequency at which power taken by the barrier equals power lost in series resistance. (GHz) | 2 | 20 | None |

video frequency in the spectrum plane.

Dynamic Range. For this paper the dynamic range is defined as the range of rf power level over which the deviation from square-law detection is less than 0.3 db. At the lower power limit this definition requires a signal/noise ratio of 2.5, which is the commonly accepted definition of Tangential Sensitivity. In order to see in mathematical terms the origin of the upper square-law limit,[1,2] the expression for low-level rectification by a two terminal device is written as

$$\frac{\Delta i}{P} = \frac{f^{(2)}}{2f^{(1)}} \left[ \frac{1 + \frac{P\, f^{(4)}}{8\, f^{(1)}\, f^{(2)}}}{1 + \frac{P\, f^{(3)}}{4[f^{(1)}]^2}} \right] \tag{2}$$

where $i = f(v)$ is the voltage-current function for the device and $f^{(1)}, f^{(2)}, f^{(3)}$, and $f^{(4)}$ are derivatives of f with respect to v. The symbol $\Delta i$ represents the incremental increase of detected current upon application of signal power P. It is clear from equation (2) that the second derivative is essential to square-law rectification. The bracketed factor shows how higher order derivatives cause deviation from square-law response.

Figure 3 shows the upper and lower square-law limits normalized to unit bandwidth for a representative device from each of the six device classes. As indicated earlier, the upper square-law limit is that power which produces a 0.3 db deviation from square law response. The lower limit is simply the noise equivalent power. Notice how bias affects the dynamic ranges of hot carrier diodes and point contact diodes. Similar bias effects apply to the other devices, but the results are not shown. The limits shown in Fig. 3 have been calculated for devices with specific geometries and, where applicable, under specific condition of bias. A similar chart can be drawn for any group of device whose design parameters are known thus providing a quantitative comparison relative to a given set of performance specifications.

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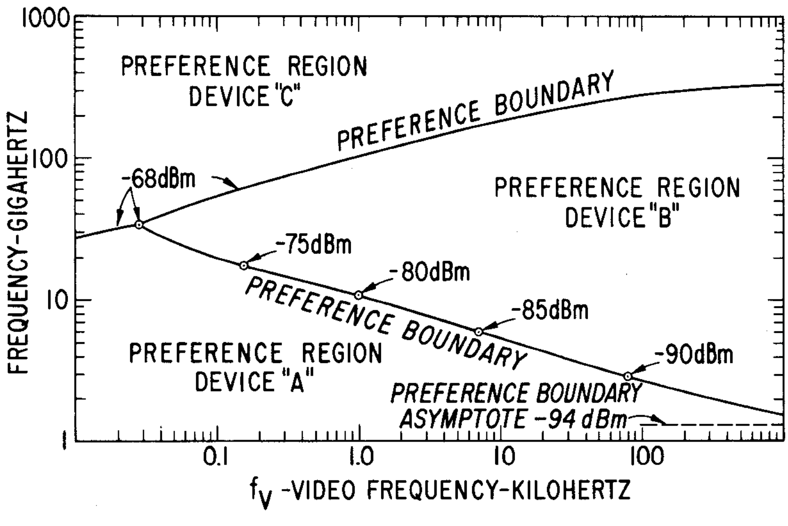


Figure 2. Preference Boundaries

for devices whose NEP contours are given in Figure 1.

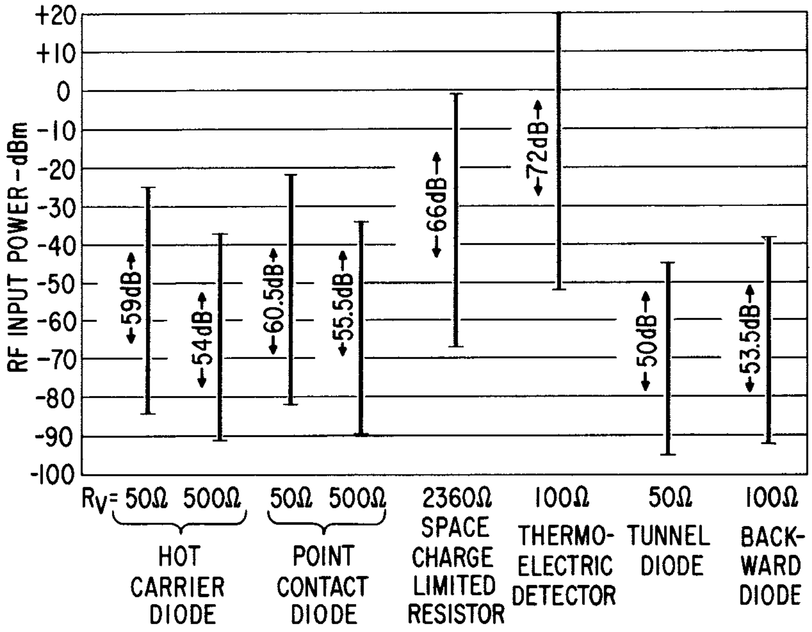


Figure 3. Dynamic Range Comparison Chart for Microwave Detectors

Conditions:

Upper Square Law Limit defined by 0.3 dB deviation.
Lower Square Law Limit defined by S/N ratio = 2.5 for a video bandwidth of 1.00 Hz.
Video frequency for above the noise corner.
Radio frequency for below the barrier cutoff frequency.
$R_v$ = Video resistance - determined by bias for barrier devices and for SCLR.