DC- and Microwave-Biased Extrinsic GaAs Photoconductors

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***Abstract*—The theoretical performance of dc- and microwave-biased extrinsic GaAs photoconductors is presented. The variables are the electrical bandwidth (1 kHz to 10 MHz) and the background photon irradiance (10^8 to 10^{16} ph/s·cm²). Experimental results taken from the literature are compared to the theoretical values. It is concluded that the theoretical performance of a microwave-biased extrinsic GaAs photoconductor exceeds that of its dc-biased counterpart, particularly at wide electrical bandwidths and/or low backgrounds.**

I. Introduction

HIGH RESISTIVITY extrinsic gallium arsenide photoconductors are well-known detectors for the 100- to 400-μ region. Such detectors are usually operated in a dc series circuit with a matching load resistor [1]–[3]. The load resistor is often several megaohms, and this value combined with the total capacitance of the circuit limits the electrical bandwidth due to a long RC time constant. Feedback amplifier techniques are sometimes used to reduce the total capacitance, increasing the electrical bandwidth [4]. For wide electrical bandwidth applications, however, the load resistor must still be reduced. This produces an impedance mismatch to the high resistivity detector which reduces its sensitivity.

Microwave-biased extrinsic GaAs photoconductors have been investigated in an effort to provide a sensitive yet wide electrical bandwidth detector [5], [6]. In the microwave-biasing method, the photoconductor is placed in the high electric-field region of a microwave cavity. Changes in the photoconductor resistance produce a change in the cavity reflection coefficient. The net result is a microwave-biased photoconductor which is capacitively coupled to its bias field. Since no dc current flows through the photoconductor, RC effects are absent. The limiting electrical bandwidth is usually the cavity bandwidth set by the loaded cavity quality factor.

In this analysis, the theoretical performance of dc- and microwave-biased extrinsic GaAs photoconductors is compared under a variety of conditions. The primary variables are the background photon irradiance (10^8 to 10^{16} ph/s·cm²) and the electrical bandwidth (1 kHz to 10 MHz). Experimental results taken from the literature are compared to the theoretical performance.

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II. Photoconductor Parameters

The high resistivity n-type GaAs photoconductor is assumed to an epitaxial layer with a square active area. The absorption cross section is calculated from the activation energy using a hydrogenic model [7]. This value is then combined with the calculated reflectivity to determine the quantum efficiency. Improvements due to integrating chambers are not included.

The photoconductor resistance is determined by the thermal- and photon-generated carrier densities, the photoconductor dimensions, and the photoconductor material parameters. That is,

$$R_D = \frac{(d/wL)}{q\mu[p_0 + \eta\tau Q_B/L]} \tag{1}$$

where d is the photoconductor height (cm), w is the photoconductor width (cm), L is the photoconductor thickness (cm), q is the electronic charge (C), μ is the photocarrier mobility (cm²/V·s), p_0 is the thermal carrier density (cm^{-3}), η is the quantum efficiency (unitless), τ is the recombination lifetime (s), and Q_B is the background photon irradiance (ph/s·cm²).

The recombination lifetime is calculated from the electron capture rate and the residual acceptor concentration. The photoconductor is assumed to be operated at 4.2K with an applied electric field of 5 V/cm. The extrinsic GaAs photoconductor characteristics used in this analysis are listed in Table I.

III. Figures of Merit

The performance of extrinsic GaAs photoconductors, regardless of the bias frequency, is analyzed in terms of the D^* figure of merit [8]. Two D^* terms are considered, each the result of a particular noise source. The first is the background noise limited D^* value given by

$$D^*_{\lambda B} = \frac{\lambda}{2hc}\left(\frac{\eta}{Q_B}\right)^{1/2} \tag{2}$$

where λ is the peak wavelength (m), h is Planck's constant (J·s), and c is the speed of light (m/s).

The second D^* term is the electronics noise limited value given by

$$D^*_{\lambda e} = \frac{q\eta G\lambda}{hc}\left(\frac{R_L A_D}{4kT_L}\right)^{1/2}(10^{-0.05F}) \tag{3}$$

TABLE I
EXTRINSIC GaAs PHOTOCONDUCTOR CHARACTERISTICS

Physical/Semiconductor Parameters		
Height (cm)	0.3	
Width (cm)	0.3	
Length (cm)	0.025	
Donor Density (cm^{-3})	2×10^{14}	
Acceptor Density (cm^{-3})	1×10^{14}	
Effective Mass (unitless)	0.0665	[2]
Activation Energy (eV)		
--Thermal	0.0051	[2]
--Photoionization	0.0058	[2]
Peak Wavelength (microns)	282	
Mobility (cm^2/V·sec)	7.5×10^4	[2]
Electron Capture Rate (cm^3/sec)	2.5×10^{-6}	
Dielectric Constant (unitless)	12	
Calculated Values		
Absorption Cross-Section (cm^2)	8.7×10^{-14}	
Absorption Coefficient (cm^{-1})	8.7	
Reflectivity (unitless)	0.3	
Quantum Efficiency (percent)	18	
Recombination Lifetime (nsec)	4	

where G is the appropriate current gain (unitless), R_L is the appropriate load resistance (Ω), A_D is the photoconductor active area (cm^2), k is Boltzmann's constant (J/K), T_L is the load resistor temperature (K), and F is the follow-on electronics noise figure (dB). This term defines the Nyquist noise of the appropriate load resistor and the follow-on electronics system.

The background and electronics noise terms are uncorrelated. Consequently, the resultant noise is the square root of the sum of individual rms noise terms. Because of this, the effective D^* term is given by

$$D^*_{\lambda\mathrm{eff}} = \left[\left(\frac{1}{D^*_{\lambda B}}\right)^2 + \left(\frac{1}{D^*_{\lambda e}}\right)^2\right]^{-1/2}. \quad (4)$$

The effective D^* is dominated by the lowest individual D^* value.

The performance of extrinsic GaAs photoconductors is often reported in terms of the noise equivalent power (NEP). This factor, while normalized to unit electrical bandwidth, is not normalized to unit active area [8]. The effective NEP is related to the effective D^* by

$$\mathrm{NEP}_{\lambda\mathrm{eff}} = \frac{(A_D)^{1/2}}{D^*_{\lambda\mathrm{eff}}}. \quad (5)$$

Two photoconductors having the same effective D^* value can have quite different effective NEP values depending upon their respective active areas. For this reason the D^* figure of merit is used herein when comparing different photoconductors measured under different conditions.

TABLE II
ELECTRICAL BANDWIDTH AND CORRESPONDING MAXIMUM LOAD RESISTOR (DC-BIASED)

Electrical Bandwidth (B)	Maximum Load Resistor $(R_L)_{max}$
1 kHz	175 MΩ
10 kHz	17.5 MΩ
100 kHz	1.75 MΩ
1 MHz	175 kΩ
10 MHz	17.5 kΩ

IV. DC-BIASED GaAs PHOTOCONDUCTORS

The dc-biased extrinsic GaAs photoconductor is assumed to be operated in a series circuit with a variable load resistor and a feedback amplifier. This arrangement yields the lowest possible capacitance and thus the highest electrical bandwidth for any load resistor value. Both the load resistor and the feedback amplifier are assumed to be operated at 4.2 K.

The load resistor is determined by the required electrical bandwidth and the amplifier capacitance. The maximum load resistor value which will allow operation with a fixed RC-limited electrical bandwidth is given by

$$(R_L)_{\max} = 0.35/BC_T \quad (6)$$

where B is the electrical bandwidth (Hz), and C_T is the capacitance of total circuit (F). Using a capacitance of 2 pF [4], the maximum load resistor for various electrical bandwidths is shown in Table II.

With the load resistor set by the electrical bandwidth, the electronics limited D^* of the dc-biased extrinsic GaAs photoconductor can be determined. Referring to (3), the appropriate current gain term is the photoconductive gain given by

$$G_{pc} = \mu\tau E/d \quad (7)$$

where E is the applied electric field (V/cm). The appropriate load resistor value in (3) is the parallel combination of the GaAs photoconductor resistance (R_D) and the load resistor set by the electrical bandwidth (6). In essence, this formalism defines the Nyquist noise of the total parallel resistance in the dc series circuit.

Using the parameters listed in Table I, a 1-MHz electrical bandwidth, and a 1-dB amplifier noise figure, the electronics limited D^* for a dc-biased extrinsic GaAs photoconductor is calculated to be $D^*_{\lambda e} = 1.5 \times 10^{12}$ cm·Hz$^{1/2}$/W. Regardless of the background limited value, the effective D^* can never exceed 1.5×10^{12} cm·Hz$^{1/2}$/W for the conditions considered.

The theoretical effective D^* for the dc-biased extrinsic GaAs photoconductor as a function of background photon irradiance with electrical bandwidth as a parameter is shown in Fig. 1. As expected, the effective D^* decreases as the electrical bandwidth increases. As the background photon irradiance decreases, the $D^*_{\lambda\mathrm{eff}}$ saturates to a value near 10^{13} cm·Hz$^{1/2}$/W. This value is consistent with the maximum D^* measured to date for a dc-biased extrinsic

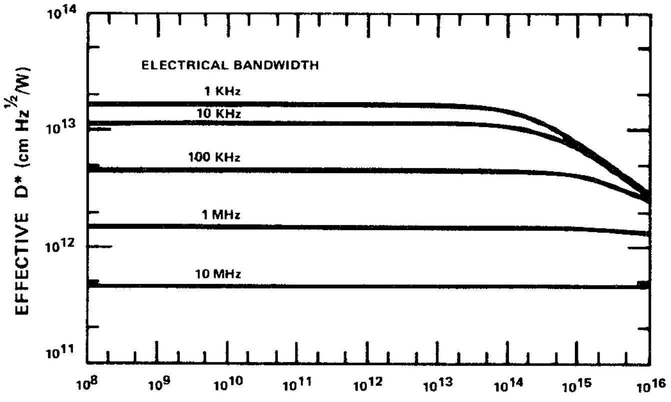

Fig. 1. DC-biased GaAs expected performance.

GaAs photoconductor, namely, 7.9×10^{12} cm·Hz$^{1/2}$/W at $Q_B\sim2\times10^9$ ph/s·cm^2 [3].

V. Microwave-Biased GaAs Photoconductors

The microwave-biased extrinsic GaAs photoconductor is assumed to be operated in an X-band microwave cavity having a characteristic impedance of 50 Ω. The signal is processed by a microwave receiver having an input impedance of 50 Ω. The limiting electrical bandwidth is assumed to be set by the loaded cavity bandwidth.

The loaded cavity quality factor and the corresponding equivalent cavity resistance are allowed to be variables which are set by the required electrical bandwidth [9]. That is

$$R_C=2\left(\frac{f_0}{B}\right)Z_C \tag{8}$$

where f_0 is the bias frequency (Hz) and Z_C is the cavity characteristic impedance (Ω). Using a 10-GHz bias frequency, the loaded cavity quality factor and the corresponding equivalent cavity resistance for various electrical bandwidths are shown in Table III.

The appropriate current gain for the microwave-biasing case is given by [9]

$$G=2\tau f_0\left(\frac{R_D\|R_C}{R_L}\right)^{1/2} \tag{9}$$

where $R_D\|R_C$ is the parallel combination of R_D and R_C. R_L is the appropriate load resistor for the microwave-biasing case, i.e., the microwave receiver input impedance of 50 Ω.

The dominant characteristic of microwave-biased extrinsic photoconductors is the high gain-bandwidth product. For example, the current gain for a microwave-biased extrinsic GaAs photoconductor having a 1-MHz electrical bandwidth is calculated from (9) to be 3.2×10^4. This extremely high value of current gain has a dramatic effect upon the electronic limited D^*, leading to a value of $D^*_{\lambda e}=5.3\times10^{15}$ cm·Hz$^{1/2}$/W for a microwave-biased extrinsic GaAs photoconductor with a 3-dB receiver. This result can be compared to $D^*=1.5\times10^{12}$ cm·Hz$^{1/2}$/W

TABLE III

Electrical Bandwidth and Corresponding Loaded Cavity Quality Factor and Equivalent Cavity Resistance (Microwave-Biased)

Electrical Bandwidth (B)	Loaded Cavity Quality Factor ($Q_L=f_0/B$)	Equivalent Cavity Resistance (R_C)
1 kHz	10^7	1000 MΩ
10 kHz	10^6	100 MΩ
100 kHz	10^5	10 MΩ
1 MHz	10^4	1 MΩ
10 MHz	10^3	100 kΩ

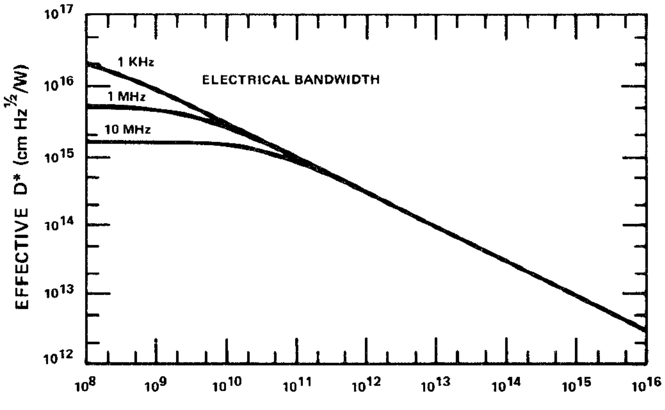

Fig. 2. Microwave-biased GaAs expected performance.

calculated for a dc-biased extrinsic GaAs photoconductor operating at the same electrical bandwidth.

The theoretical effective D^* for a microwave-biased extrinsic GaAs photoconductor as a function of background photon irradiance level with electrical bandwidth as a parameter is shown in Fig. 2. As expected the effective D^* decreases as the electrical bandwidth increases. As the background decreases, the effective D^* continues to rise. Theoretical effective D^* values greater than 10^{15} cm·Hz$^{1/2}$/W are shown to be feasible at low background irradiance levels.

Experimental measurements on microwave-biased extrinsic GaAs photoconductors have been taken with an unfiltered room temperature background incident upon the detector [5], [6]. The signal source was an HCN laser operating at 337 μm. Under these conditions, the maximum D^* value measured was 1.4×10^9 cm·Hz$^{1/2}$/W [6]. This relatively low D^* value was the result of excessive noise attributed to the microwave bias source [10]. No low background measurements have been reported on microwave-biased extrinsic GaAs photoconductors.

Although bias source noise has dominated microwave-biased extrinsic GaAs photoconductor measurements reported to date, such noise can be significantly reduced. Using a cavity-stabilized Gunn diode source, microwave-biased mercury-doped germanium photoconductors have exhibited a D^* of 5.1×10^{12} cm·Hz$^{1/2}$/W in the 8- –14-μ region [11]. This D^* value is a factor of 2 below the BLIP

TABLE IV

SUMMARY OF THEORETICAL/EXPERIMENTAL PERFORMANCE OF DC- AND MICROWAVE-BIASED EXTRINSIC GaAs PHOTOCONDUCTORS

	1 kHz	10 MHz
1×10^{16} photons/sec·cm^2	D* (DCB) = 2.8×10^{12} a	D* (DCB) = 4.7×10^{11} a
	D* (DCB) = 4.5×10^{11} [2]	D* (DCB) = NO DATA
	D* (MWB) = 3.0×10^{12} a	D* (MWB) = 3.0×10^{12} a
	D* (MWB) = NO DATA	D* (MWB) = 1.4×10^{9} [6]
1×10^{8} photons/sec·cm^2	D* (DCB) = 1.2×10^{13} a	D* (DCB) = 4.7×10^{11} a
	D* (DCB) = 7.9×10^{12} [3]	D* (DCB) = NO DATA
	D* (MWB) = 1.6×10^{16} a	D* (MWB) = 1.7×10^{15} a
	D* (MWB) = NO DATA	D* (MWB) = NO DATA

NOTES:

D* units are cm Hz$^{1/2}$/W

DCB--dc-biased

MWB--microwave-biased

a--theoretical value, this work

[ ]--experimental data closest to conditions listed

limit for the measured background photon irradiance level of 5.4×10^{12} ph/s·cm^2. When low noise bias sources are used with microwave-biased extrinsic GaAs photoconductors, D^* values exceeding 1×10^{14} cm·Hz$^{1/2}$/W should be possible under similarly low background conditions.

IV. SUMMARY AND CONCLUSIONS

The theoretical performance of dc- and microwave-biased extrinsic GaAs photoconductors is presented in terms of the D^* figure of merit. The variables are the electrical bandwidth (1 kHz–10 MHz) and the background photon irradiance (10^8–10^{16} ph/s·cm^2). Experimental results taken from the literature are compared to the theoretical values.

The dc-biased extrinsic GaAs photoconductor is seen to be electronics noise limited at low backgrounds and/or wide electrical bandwidths. The microwave-biased extrinsic GaAs photoconductor is seen to be capable of background noise limited performance under most conditions. The theoretical performance of both detectors at the extremes of the conditions considered herein is summarized in Table IV.

It is concluded that the theoretical performance of a microwave-biased extrinsic GaAs photoconductor is superior to its dc-biased counterpart, particularly at wide electrical bandwidths and/or low backgrounds. The large gain-bandwidth product achievable with microwave-biasing is seen to be the primary reason for its outstanding theoretical performance.

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