CONCEPTUAL DESIGN AND APPLICATIONS OF HgCdTe INFRARED PHOTODIODES FOR HETERODYNE SYSTEMS

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SUMMARY

HgCdTe photodiodes represent an important component for heterodyne detection systems operating in the 9 to 11μm CO_2 laser wavelength region. Their successful fabrication requires thorough understanding of the physical properties of the basic materials. The implementation of controlled industrial processes ensures the yield of predictable and repeatable detector characteristics to satisfy today's discriminating systems' demands for high cutoff frequencies, quantum efficiency, and reliability. The most salient production steps and diode characteristics will be described. Measured results from present production units will be presented.

INTRODUCTION

Numerous CO_2 laser applications, in particular those dealing with heterodyne detection at 10.6μm, are largely responsible for the generally increased interest in fast photodiodes for this wavelength region.

As previously reported (1), (2), (3), HgCdTe photodiodes have inherent cutoff frequency capabilities beyond one GHz. This is rendered possible by the normal value of the materials permittivity and the ability to create a junction of very low capacitance. In fact, because of the very high electron mobility in narrow-bandgap semiconductors, the dynamic characteristics of the minority carriers are not expected to become significant limiting mechanisms of the diode. Furthermore, the high value of the absorption coefficient permits excellent optimization of quantum efficiency and cutoff frequency.

The extent of studies conducted during the past decade on the metallurgy of the materials and on the diode technology have enabled us to gain a better understanding of the factors affecting the diode characteristics, performance, and reliability. Thanks to the knowledge gained on the diodes and on their interdependent parameters, it is now possible to optimize the development of a diode for a given application.

PHOTODIODE OPTIMIZATION (77K) FOR A 10.6μm HETERODYNE RECEIVER

The heterodyne receiver signal-to-noise ratio can be expressed using the passive elements of the diode equivalent circuit (Fig.1), including shunt conductance (G_D), junction capacitance (C_D), series resistance (R_s) as well as the signal and noise generators and the preamplifier (4),(5), as shown in Eq.1:

$$\frac{S}{N} = \frac{\eta \; q \; P_{SIG}}{h\nu \; \Delta f \left\{ 1 + \frac{I_d}{I_{Lo}} + \frac{2k(T_D + T'_{PA})}{I_{Lo}} \left[G_D(1 + R_S G_D) + R_S C_D^2 \omega^2 \right] \right\}} \qquad (1)$$

where η = the quantum efficiency which must be maximized for the wavelength region of interest

P_{SIG} = signal power

I_d = dark current

I_{LO} = local oscillator induced current

T_D = diode temperature

T'_{PA} = preamplifier noise temperature

Quantum efficiency

Quantum efficieny (η) is defined as the ratio of carriers crossing the junction to the total number of incident photons. It is limited by:

- reflection losses on the semiconductor surface. These losses can be reduced through antireflection coating

- electron-hole recombination in the bulk before reaching the junction. To minimize this effect, the carriers must be generated as close as possible to the junction either through the creation of superficial junctions or by utilizing the transparency effect resulting from the doping of the n-surface of the p-n junction. The transparency effect (1) is particularly prominent in narrow-bandgap semiconductors

- surface recombination which can be reduced through surface passivation or by avoiding carrier generation in the bulk through utilization of the transparency effect

Cutoff Frequency

The HgCdTe detector response varies as a function of frequency. Three factors contribute to the limitation of the usable cutoff frequency (6), (Fig.2):

a. <u>Diffusion effects.</u>

When the depletion region is narrow with respect to the absorption length (case of the very mildly biased junction), only those carriers created within less than one diffusion length will reach the junction and the time required for this action to take place limits the speed. The corresponding cutoff frequency is

$$f_{c_{DIFF}} = \frac{2.4\, D\, \alpha^2}{2\pi} \qquad (2)$$

where D = diffusion coefficient of minority carriers
α = photon absorption coefficient

For example: for $\alpha = 3 \times 10^3\ cm^{-1}$ and D near unity, the cutoff frequency is limited to about 10 MHz.

b. Transit time in the depletion region.

The widening of the depletion region causes an increase in the number of carriers generated. The speed of these carriers is increased by the electric field and the corresponding cutoff frequency is given by

$$f_{c_{DRIFT}} = \frac{2.4\, v_s}{2\pi w} \qquad (3)$$

where w = width of the depletion region

v_s = carrier speed, reaching its limit near $10^7 \, cm\, s^{-1}$

Thus, for $w = 3\mu m$, the cutoff frequency is in excess of 10 GHz.

c. Junction capacitance.

The photodiode equivalent circuit (Fig.1) shows the presence of a cutoff frequency limitation through the $R_L C_D$ time constant, wherein R_L is the diode load resistance and C_D the junction capacitance. For a load of 50 ohms and 1 pF capacitance, the cutoff frequency is approximately 3.2 GHz.

The improvement of the cutoff frequency of a photodiode therefore requires the following efforts:

1. Reduction of the junction capacitance by reducing the surface area and the doping level on either side of the junction.

2. Widening of the depletion region and bringing it closer to the surface. This also requires low doping level, a junction depth adapted to the extension of the depletion region and to the absorption length, and elevated breakdown field strength.

These conditions can be simultaneously met, as shown in Fig.3. A doping level of $2 \times 10^{14} cm^{-3}$ and bias of about -1V lead to a depletion region width of about $1/\alpha$, that is, $3\mu m$. This, in turn, results in the following advantages:

- high quantum efficiency, if the junction depth is of the same order of magnitude (3 to $5\mu m$)

- high cutoff frequency resulting from the short transit time in the depletion region (3×10^{-11}s) and the low junction capacitance (1 pF for an area of $2 \times 10^{-4} cm^2$)

Planar Technology

The planar technology developed and implemented for the fabrication of HgCdTe photodiode arrays and matrices (7) presents numerous advantages for the manufacture of fast photodiodes, such as:

- protection of the edges around the junction, thus reducing leakage currents and permitting the use of high bias voltages

- passivation of the sensitive area, which reduces internal reflection losses and surface recombination. It also increases the reliability by diminishing the effect of external factors

The p-type HgCdTe material is prepared through recrystallization at the solid state or through epitaxial deposition and isothermal diffusion. The purity of the basic material must be very high in order to attain the desired low doping levels.

Substrate preparation (Fig.4) includes mechanical polishing and cleaning in a bromine-alcohol solution, followed by passivation with a ZnS deposition. The diffusion apertures are developed through localized chemical etching of this layer. Two methods are employed to form the junction: mercury diffusion and ion implantation. A passivation layer of ZnS is then applied which, in turn, is etched to prepare the contacts. The contact areas are formed through a deposit of gold-chromium, and this is followed by overall passivation.

This technology permits the fabrication of all kinds of geometries and photodiode groupings (square, rectangular, or round sensitive areas, single-element detectors, arrays, quadrants, and small matrices).

Photodiode Installation in Cryostat

The method used for mounting the photodiode in its cryostat is of primary importance. On the one hand, one must reduce parasitic capacitance and, on the other hand, it is essential to:

- reduce the inductance of the connections (L_s)
- feed the IF output through the cryostat, using a coaxial cable
- protect the photodiode against electro-magnetic interference

These goals are reached by installing the photodiode in a housing which serves to support and protect it while, at the same time, providing the link to a coaxial output connector (Fig.5). A miniature coaxial cable with a stainless steel sheath connects this housing to the output of the cryostat.

RESULTS

High-speed HgCdTe photodiodes (Class C4) for heterodyne detection at 10.6μm from present production exhibit the following characteristics:

Sensitive area: between 10^{-4} and $2 \times 10^{-4} cm^2$
Quantum efficiency: 50 to 60%
Breakdown field strength (at 1mA): in excess of 2V, reaching or exceeding 3V on certain diodes
Max. reverse dynamic resistance: about 100 kohms
Series resistance: 10 ohms

Analysis of the capacitance variation with increasing bias voltage discloses the presence of a steep junction (varies as $1/c^2$ as a function of reverse bias voltage) (Fig.6) and of a doping level of about 1 to $2 \times 10^{14} cm^{-3}$. This confirms the high purity level of the starting material.

The particularly high breakdown field strength which we measured (Fig.7), reveals that the leakage currents around the edges of the junction are minimized by the passivation layer. As predicted by mathematical models, cutoff frequencies in excess of 1 GHz have been achieved with a reverse bias value of -1V (Private communication from Lemaine, Laboratoire de Spectroscopic

Hertzienne, L.A.C.N.R.S. 249 U.S.T.L.)(Fig. 8), while heterodyne detection operation with these detectors was reported at frequencies of 8.7 GHz (8) (Unpublished report by J. P. Sattler et al., U.S. Army, Harry Diamond Laboratories).

Reliability

Reliability tests to military specifications, including cycling up to temperatures of 80°C, which were conducted for periods of several thousand hours without degradation of the diode characteristics, testify to the high degree of reliability of these components. This is further confirmed by the fact that detectors, which have seen operation in the field for over 10 years, are still operating (Private communication from B. J. Peyton of AIL). The use of a passivation layer is primarily responsible for the immunity to external disturbing factors and, in particular, to short wavelength radiation.

Operation at Temperatures in Excess of 77K

The proper operation of a HgCdTe photodiode at temperatures in excess of 77K requires the following conditions:

1. High quantum efficiency at this temperature at 10.6μm. This can be achieved by selecting the composite material so that the absorption coefficient will always be 1000 or higher.

2. Saturation current below the level of the local oscillator current, the latter being generally on the order of 1 to 3 mA.

3. A reverse dynamic resistance (R_D) selected so that:

$$R_D I_{LO} >> \frac{2kT}{q}$$

Numerous studies conducted in our laboratories (DRET contract no. 76/422) on detectors operating at temperatures in excess of 77K enabled us to reach R_oA products at $10^{-2}\Omega cm^{-2}$ at 140K for a spectral peak wavelength of 10.5μm. These detectors can operate in a heterodyne mixer without noticeable degradation of their performance characteristics, when compared to those normally experienced at 77K. "Long wavelength" detectors ($\lambda_p \simeq 14\mu m$ at 77K) were measured at temperatures within the operating range of thermoelectric coolers (S.A.T. internal report). In accordance with our predictions regarding the variation of the intrinsic concentration as a function of temperature and based on the characteristics measured at 77K, these detectors exhibit saturation current levels of about

20mA at 200K and reverse dynamic resistance of about 40 ohms. Calculations disclose a degradation of the heterodyne sensitivity on the order of 10 dB under these conditions.

Figure of Merit (Heterodyne Quantum Efficiency)

In order to characterize the performance of a heterodyne detector, one can include all degradation factors into a single parameter: the heterodyne quantum efficiency (η'). Referring back to Eq.1, we obtain:

$$\eta' = \eta \left\{ 1 + \frac{I_d}{I_{Lo}} + \frac{2k(T_D + T'_{PA})}{I_{Lo}} \left[G_D(1 + R_S G_D) + R_S C_D^2 \omega^2 \right] \right\}^{-1} \qquad (4)$$

where η' is a function of the local oscillator (L.O.) induced photocurrent, the IF frequency and the detector characteristics. The maximum value for a given intermediate frequency is obtained for optimum local oscillator power and detector reverse bias conditions. It must be noted that it is not possible to indefinitely increase the local oscillator power to minimize the influence of the parasitic effects of the diode and preamplifier, as this would lead to saturation and thus reduce the quantum efficiency. This can occur at local oscillator current levels in excess of a few milliamperes (Fig.9). Degradation of quantum efficiency can also be observed when comparing it to the quantum efficiency measured at very low frequencies. This is caused by the fact that only those carriers generated in the depletion region can be used at very high frequencies. It is, therefore, possible to notice a variation of the heterodyne quantum efficiency as a function of detector reverse bias. The low-frequency value of quantum efficiency is again reached when the depletion region extends very near to the detector surface.

Values of heterodyne quantum efficiency on the order of 40% were measured in the laboratory for detectors whose low-frequency quantum efficiency was 50 to 60%. These figures confirm the fact that, by optimizing the operating point of the photodiode, the degradation will only be very small.

CONCLUSION

HgCdTe photodiodes, optimized for operation at high frequencies, are manufactured through a controlled, repeatable process. They exhibit excellent I-V characteristics which permit the application of high reverse bias voltages, thus yielding at the same time high cutoff-frequency capability and high heterodyne sensitivity.

These detectors can be used in many different systems operating in the 9 to 11μm wavelength region, such as optical radars, telecommunication links, and interferometers. An important fringe benefit lies in their great reliability for terrestrial as well as for aerospace applications.

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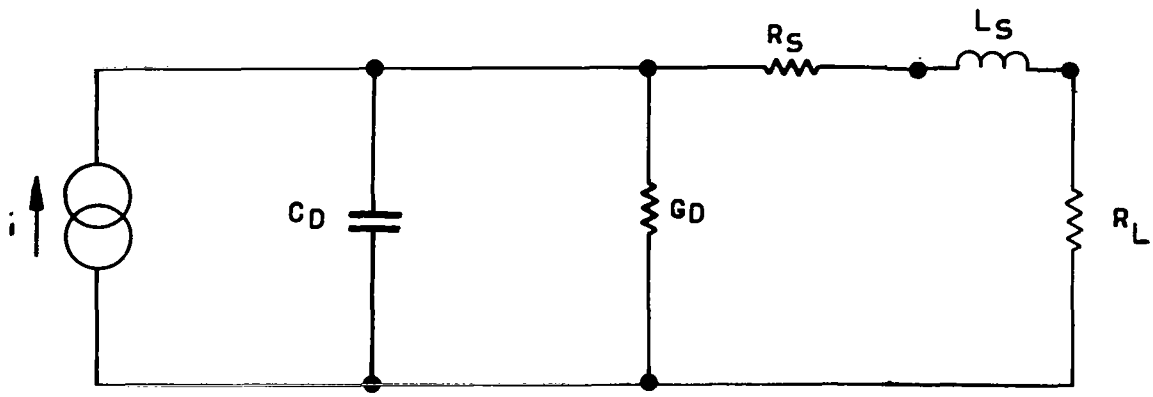

Figure 1.- Photodiode equivalent circuit.

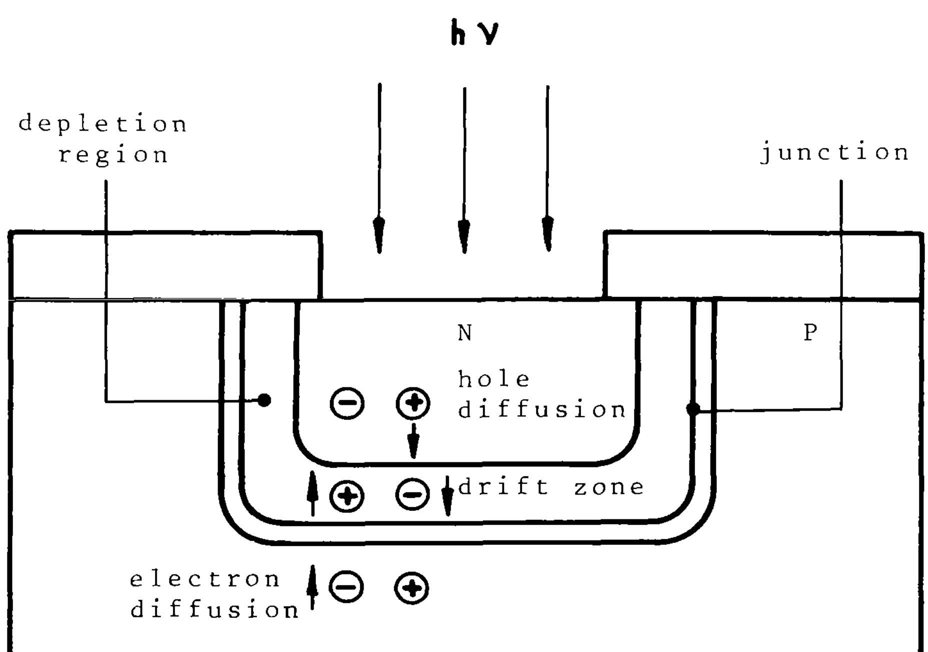

Figure 2.- Photon-induced current generation process in photodiode (junction depth = photon absorption length).

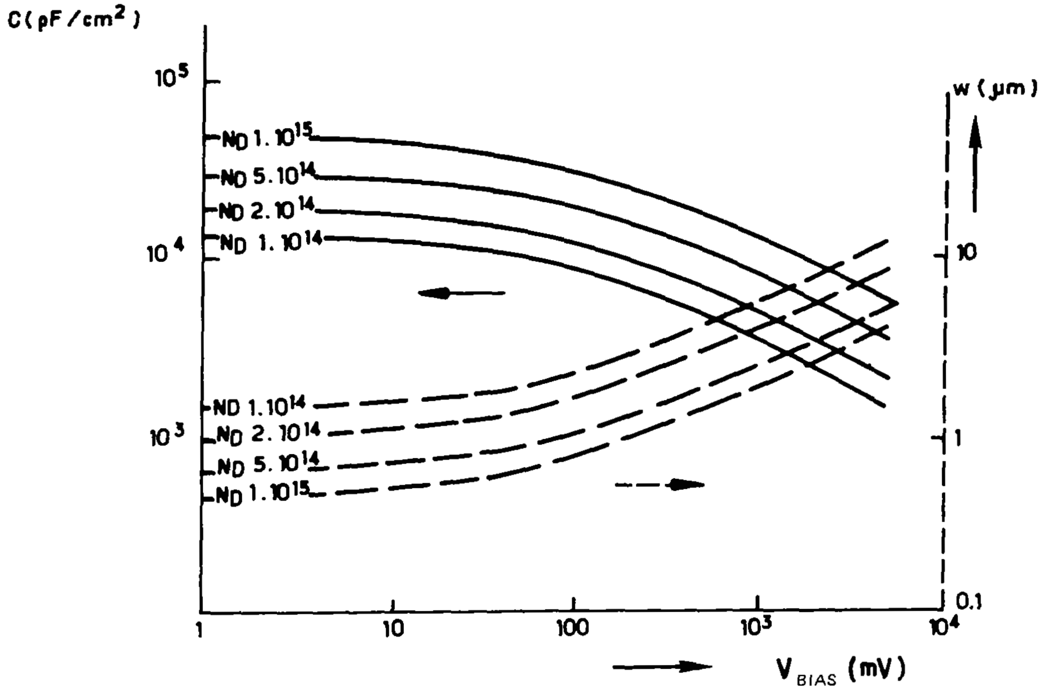

Figure 3.- Junction capacitance and depletion zone width vs. bias voltage for different n. doping levels in HgCdTe photodiode.

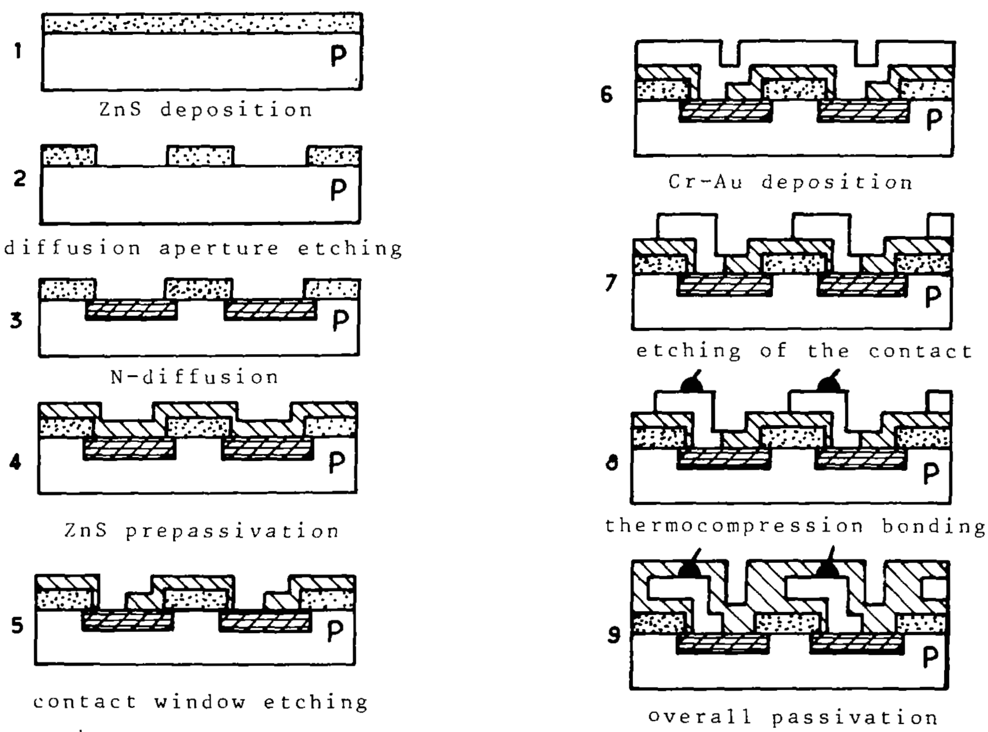

Figure 4.- Planar technology.

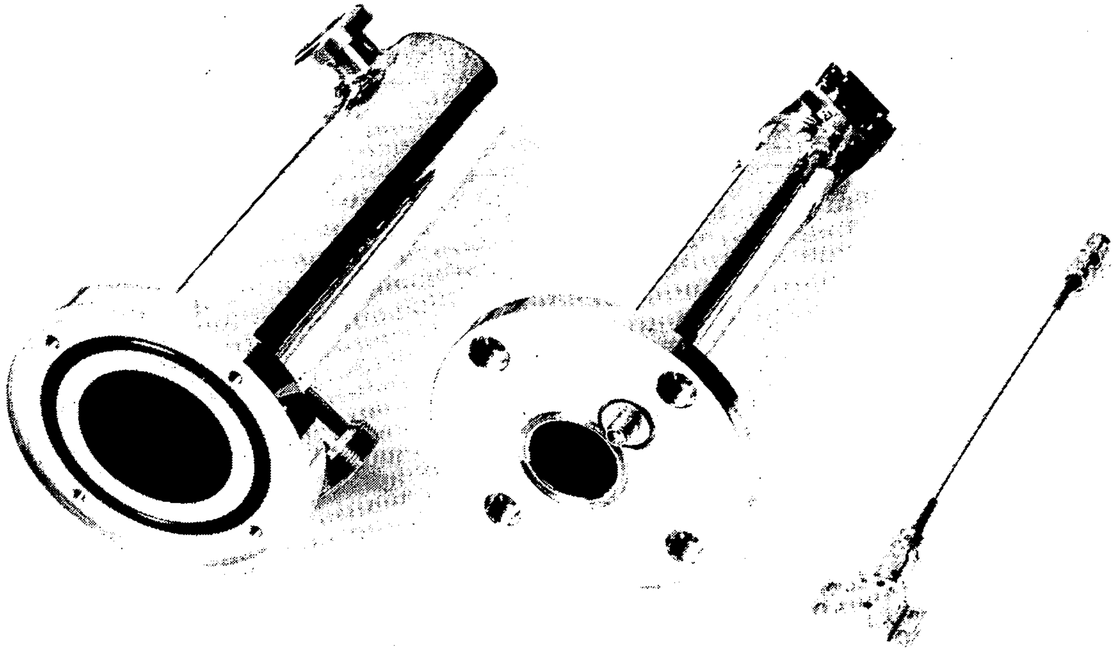

Figure 5.- Detector housing.

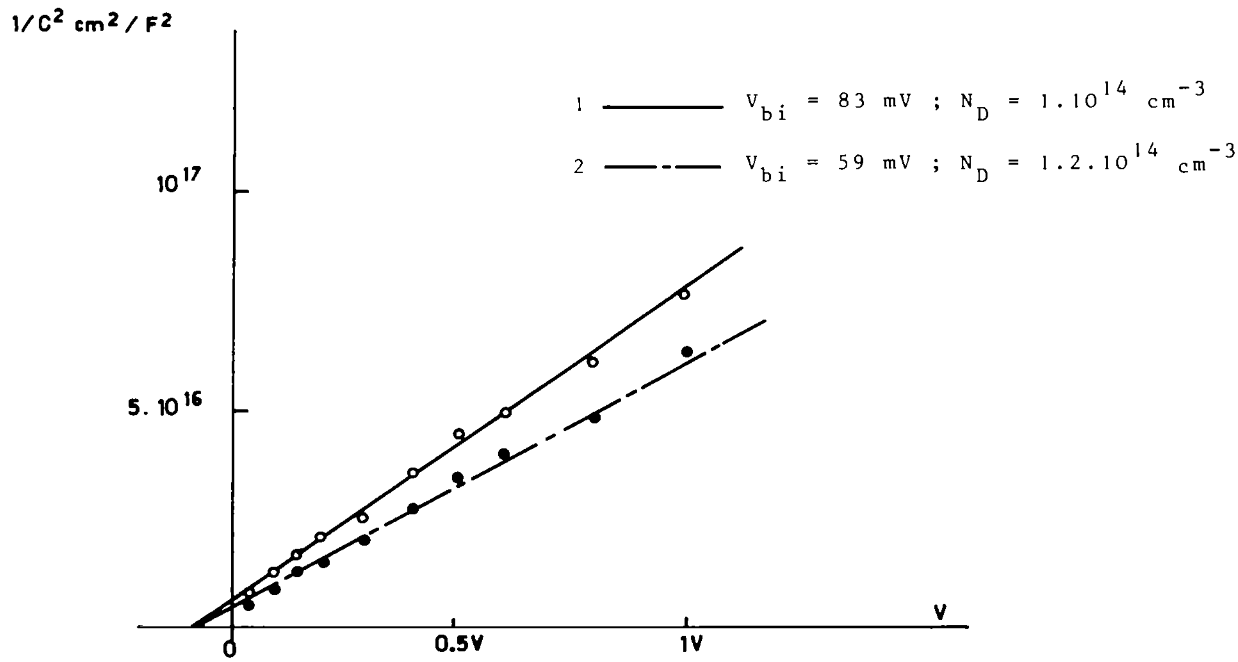

Figure 6.- Doping level calculations from C(V) plots.

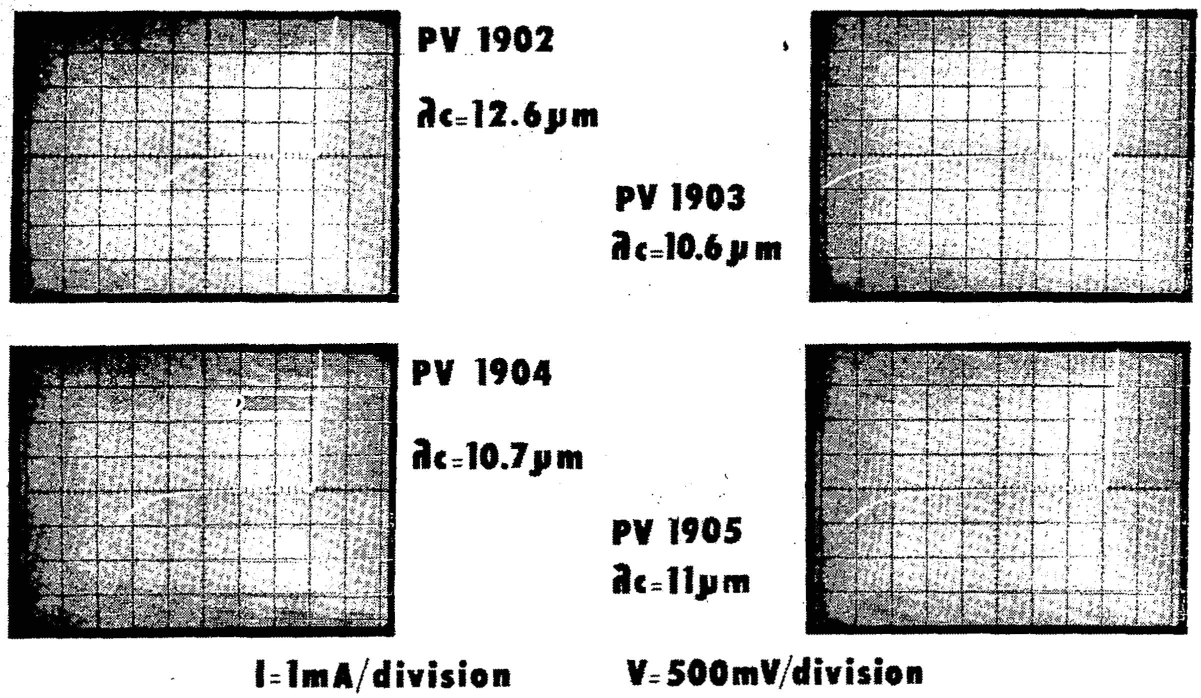

Figure 7.- I(V) characteristics of some wide bandwidth detectors.

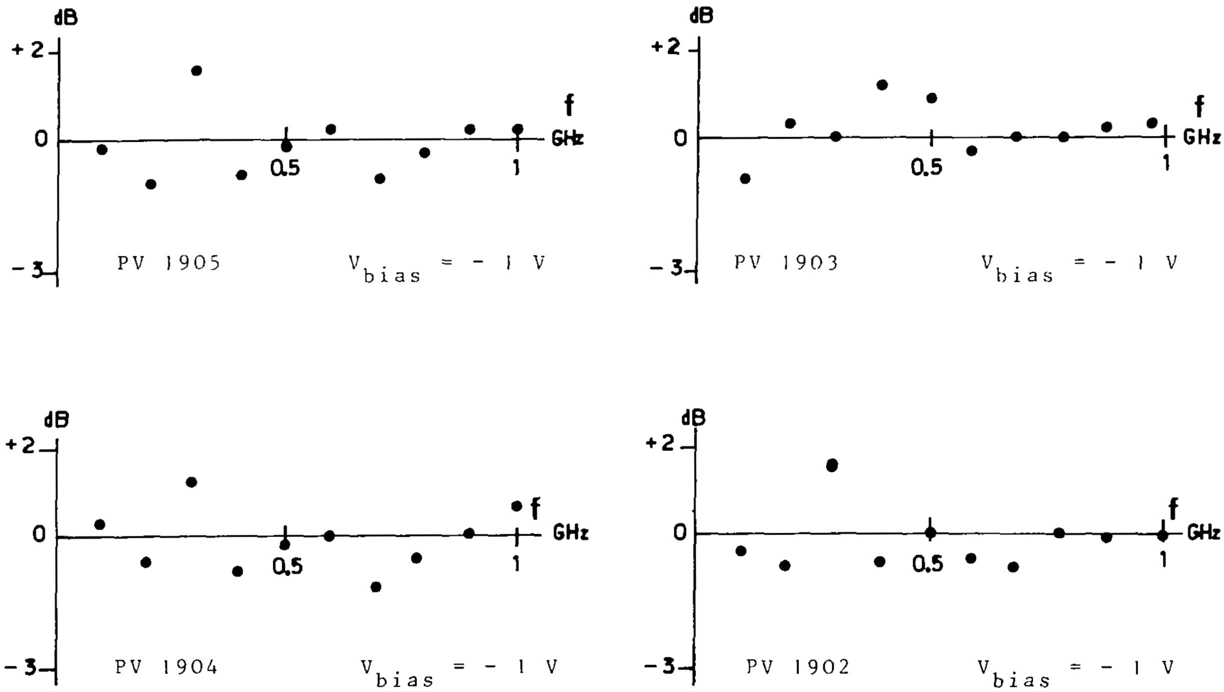

Figure 8.- Frequency response of some 10-μm photodiodes.

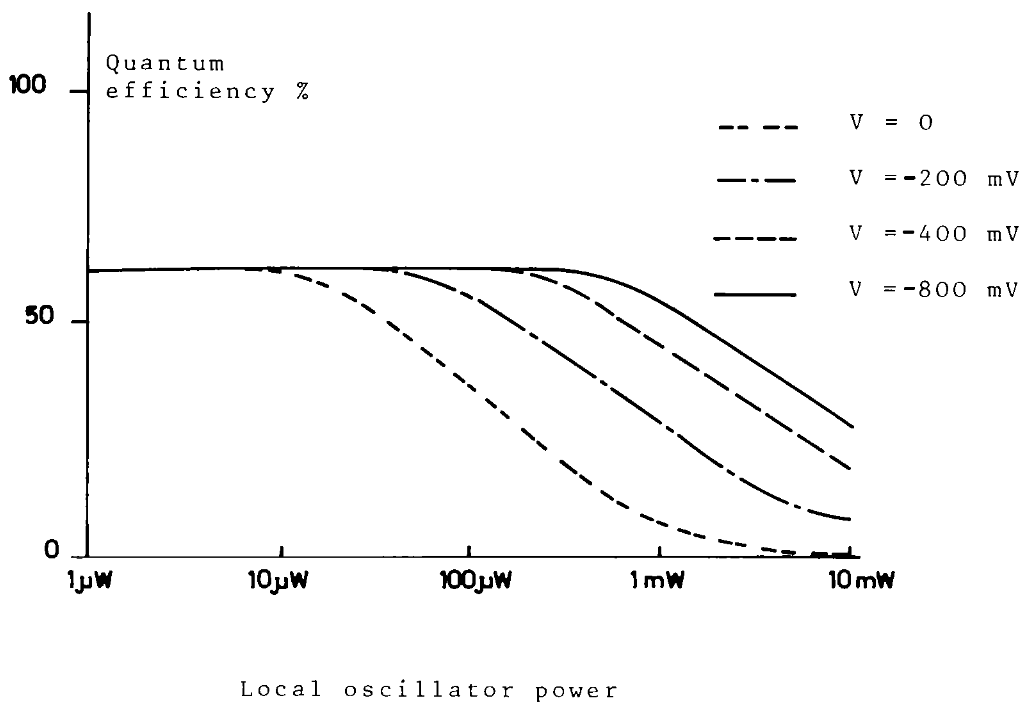

Figure 9.- Quantum efficiency vs. local oscillator power for various values of reverse bias.