# Fast Microwave Detectors Based on the Interaction of Holes with Phonons

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***Abstract*—Experimental results and a proposed model are discussed in this paper on a new microwave detector which has subnanosecond response times and a pulsed power measuring capability between 0.5 W and > 10 kW for a frequency band larger than 0–50 GHz. Our model suggests that electromagnetic energy is absorbed by holes in p-type germanium (Ge). This absorption increases the mobile hole temperature above the lattice temperature. The absorbed energy is determined by measuring the change in average mobility of the holes in the nonequilibrium state.**

**We experimentally observed greater than > 50-V output pulses for kilowatt microwave input pulses to the detector and a bias current of 1 A. The detector exhibited a linear response between 0.5 W and 1 kW. We propose that the voltage pulses in the p-type Ge detector are caused by nonequilibrium holes exchanging energy with the phonons in the crystal lattice. This energy exchange modulates the hole mobility.**

## I. Introduction

BETTER devices are needed for measuring the outputs of high pulsed power microwave sources such as the virtual cathode oscillator (VIRCATOR), relativistic magnetron, gyrotron, etc. A new class of detectors is based on transducers which exhibit picosecond response to relatively high-pulsed microwave fields. Our experimental results show that microwave power changes the hole mobility in good quality 20-Ω·cm p-type Ge. We have observed a 60:1 change in the mobility of holes when 10-kW microwave pulses are applied to our detector. The mobility change results in a 60-V pulse when a 1-A bias current is applied to the detector. Based on our proposed model, we believe that the intrinsic response time of this type detector is less than 10 ps.

These detectors are based on the heating of carriers in semiconductors placed in high electric fields ( > 1 V per μm). An excellent treatise on the transport of mobile carriers in the presence of large electric fields in semiconductors was developed by Conwell [1]–[3]. The proposed mechanisms for the change in hole mobility in our detectors is based on a computer model that we developed using Conwell's theoretical formulation. Our major contribution is to identify the mechanisms causing the effect first observed by Rayzer and Tsopp [5].

The first to build and successfully operate a bulk Ge (hot-carrier) detector were the Russians, Rayzer and Tsopp [5]. They built and successfully operated a volume effect Ge hot-carrier detector for measuring high-power microwave pulses of nanosecond duration. At 35 GHz, the output of the Russian detector is approximately the same as ours for the same input pulsed power levels and bias current pulse.

Harrison *et al.* [6] have studied another microwave detector called the hot-carrier diode. This is not to be confused with the hot-carrier Ge detector discussed in this paper. A more recent report on the hot-carrier diode is in a paper by Kikuchi and Oshimoto [7] at the National Defense Academy in Japan.

This paper proposes a mechanism for our observed mobility variation. It also gives our design of the hot-carrier Ge bulk detector with experimental results. In addition, we discuss a new fast technique for measuring the change in hole mobility.

## II. A Computer Model of Hot-Carriers in Nonpolar Semiconductors

We propose that mobile holes in Ge are brought out of equilibrium with the crystal lattice by microwave pulses with microsecond or less duration. This is the basis of our new microwave detector. To support our proposal, we give a review of the physics of hot-carriers in semiconductors with the results of a computer analysis. We calculate the change in resistance of p-type Ge for a given amount of power absorbed per carrier.

The mobility of electrons and holes in a crystal lattice is determined by their effective temperature and interaction with the various scattering mechanisms. In the presence of high electric fields, optical and acoustical phonons are the dominant scattering particles in 2 Ω·cm or larger resistivity Ge crystals. The effect of these scatters causes the average velocity of the carriers to deviate from a linear field relationship and to saturate. Using curves found in Sze [8], the fields are tabulated in Table I at the point where the velocity starts to deviate from linearity. The tabulated results suggest that the carrier velocity in p-type Ge deviates from linearity at low fields. The power absorbed per carrier is monotonically related to the electric field. Comparing the three materials, the conductivity of Ge, which is proportional to drift velocity, is most affected by low power absorbed per carrier. This suggests that we use p-type Ge to build a microwave detector whose conductivity varies with reasonable levels of absorbed power.

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TABLE I
FIELDS AT WHICH THE VELOCITY FIELD CURVES DEVIATE FROM A LINEAR RELATIONSHIP AND APPROACH A SATURATION VELOCITY

| Material | Type | Field V/cm | Saturation Velocity cm/s |
|---|---|---|---|
| Ge | p | 400 | 5e6 |
| Ge | n | 1000 | 5e6 |
| GaAs | n | 1600 | 5e6 |
| Si | p | 6000 | 1e7 |
| Si | n | 3500 | 1e7 |

Experimentally and theoretically, the lattice mobility in Ge varies according to the following equations:

$$\mu_p = 1.05 \times 10^9 T_l^{-2.33} \tag{1}$$

$$\mu_n = 4.90 \times 10^7 T_l^{-1.66}. \tag{2}$$

These equations assume that the mobile carriers are in equilibrium with the lattice. This is evident because (1) and (2) are only functions of the lattice temperature $T_l$. In the presence of high electric fields, mobility is a function of both carrier and lattice temperatures. The carriers are not in equilibrium with the lattice. To model the nonequilibrium problem, we must express the mobility in terms of both the lattice and carrier temperature. The expression in our computer program for the mobility of holes in a nonequilibrium state is obtained from Conwell's [1]–[3] papers. Conwell [2] derives the following general expression for mobility:

$$\mu = (q/m)\int_0^\infty \left(\frac{1}{p^2}\frac{d}{dP}(P^3\tau)f(P)\right) dP. \tag{3}$$

The momentum distribution function $f(P)$ is a function of carrier temperature. The relaxation time $\tau$ is a function of a lattice temperature. In (3), $q/m$ is the carrier charge to mass ratio and $P$ represents the carrier momentum.

In our computer analysis, we use the Maxwell–Boltzman distribution

$$f(P) = \frac{4\pi}{m^3}\left(\frac{m}{2\pi KT_c}\right)^{3/2} P^2 \exp\left(\frac{P^2}{2mKT_c}\right). \tag{4}$$

As pointed out by Pinson and Bray [4], the distribution for holes is strongly displaced towards higher carrier energies for fields greater than 50 V/cm and becomes non-Maxwellian. Fields much greater than 50 V/cm are necessary to change the initial Maxwellian distribution of electrons. As a result, it is expected that the hole mobilities that are calculated from this theory will not be as accurate as the electron mobilities. Conwell's [1] and our calculated mobility versus field curves agree with these findings.

In the above expressions, $T_c$ is the carrier temperature, $m$ is the effective mass of the holes ($\sim 0.3\ m_0$), and $\tau$ is the zero field relaxation time for a given lattice temperature. In terms of the acoustical and optical relaxation times for phonons

$$1/\tau = 1/\tau_{ac} + 1/\tau_{op}. \tag{5}$$

Assuming that the phonon number is a Plank distribution, and using first-order perturbation theory, Conwell [1] shows that

$$1/\tau_{ac} = \frac{\sqrt{2E/m}}{4l_{ac}}\left(\frac{2KT_l}{CP}\right)^4 \int_0^{CP/KT_l} U^4 \coth U dU \tag{6}$$

$$1/\tau_{op} = \frac{(E_{op}/E_{ac})^2}{2l_{ac}} \frac{\theta/T_l}{\exp(\theta/T_l)-1}\sqrt{\frac{2}{m}}X \cdot \left\{\sqrt{E+K\theta} + \exp(\theta/T_l)\sqrt{E-K\theta}\, U(E-K\theta)\right\} \tag{7}$$

$$E = p^2/2m \tag{8}$$

and $u(k)$ is the unit step function. A characteristic temperature is $\theta$, which is approximately 400 K for p-type Ge. The symbol $l_{ac}$ represents the mean free path length. $C$ is the sound velocity. For a good fit to (1), when the lattice temperature is equal to the carrier temperature, we let $l_{ac} = 0.26$ µm, $(E_{op}/E_{ac})^2 = 4$, and $C = 5E5$ cm/s. The lattice temperature in the above expression is represented by the symbol $T_l$.

For the theory to be useful, we develop an expression for $\Delta R/R$, the fractional change in resistance of the Ge crystal for a given lattice temperature and microwave power absorbed per carrier. The ratio $\Delta R/R$ is a measure of the response of the detector material to the microwave energy. A larger $\Delta R/R$ implies that a detector constructed from the material will be more sensitive to a given amount of power absorbed per carrier. A little algebra shows that

$$\Delta R/R = (1 - \mu_{p0}/\mu_p) \tag{9}$$

where $\mu_p$ is the mobility of holes for a given amount of microwave power absorbed per carrier and $\mu_{p0}$ is the equilibrium mobility. The ratio $\Delta R/R$ is independent of crystal geometry. To complete the formulation, we need a way to estimate the mobility for a given amount of power absorbed per carrier. Evoking Ohm's law, the power absorbed per carrier becomes

$$P/N = q\mu_p p\tilde{E}^2. \tag{10}$$

Assuming that the average power absorbed per carrier is dissipated by the acoustical and optical phonon fields, we have an additional energy balance equation for steady-state

$$P/N + \left\{\frac{dE}{dt}\right\}_{ac} + \left\{\frac{dE}{dt}\right\}_{op} = 0 \tag{11}$$

where Conwell shows that

$$\left\{\frac{dE}{dt}\right\}_{ac} = \frac{-8}{\sqrt{\pi}}\frac{\sqrt{2KT_l/m}}{l_{ac}} mc^2 \left(\frac{T_l}{T_c}\right)^{-3/2} \cdot (1 - T_l/T_c) D \tag{12}$$

$$\left\{\frac{dE}{dt}\right\}_{op} = \frac{-2}{\sqrt{\pi}}\frac{\sqrt{2KT_l/m}}{l_{ac}} K\theta \frac{(E_{op}/E_{ac})^2 \theta/T_l}{2[\exp(\theta/T_l)-1]} X \cdot \left(\frac{T_l}{T_c}\right)^{-1/2} \frac{\theta}{2T_c} K_1\left(\frac{\theta}{2T_c}\right)\left[\exp\left(\frac{\theta}{T_l} - \frac{\theta}{T_c}\right) - 1\right] D. \tag{13}$$

The Bessel function of the second kind is represented by the symbol $K_1$. To fit the theory to the experimental mobility versus field curves found in Conwell [3], we

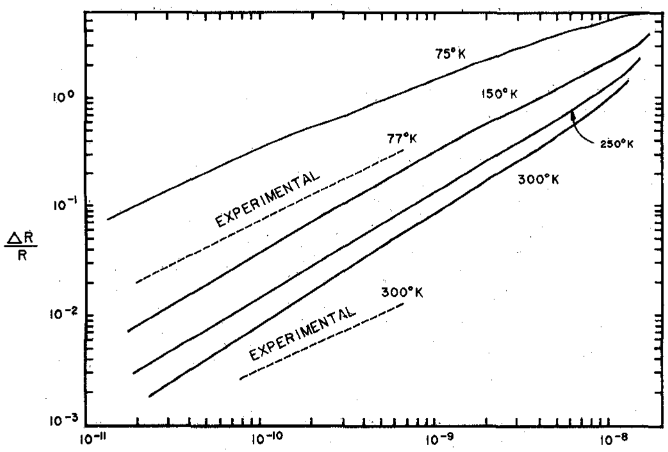

Fig. 1. Theoretical detector response.

introduced a factor $D$ in the above equations. This factor is approximately 1.E-6 in our program, an unexpectedly small number.

We have selected to plot $P/N$ versus $\Delta R/R$ as depicted in Fig. 1. Equation (11) is used to calculate $P/N$ and (9) is used to calculate $\Delta R/R$. The two equations are a parametric set of equations for $P/N$ and $\Delta R/R$ in terms of carrier temperature for a given lattice temperature.

Equation (11) is an energy rate equation. The right-hand side of the equation is approximately zero for time variations greater than the average energy relaxation time $\tau$. Conwell [1] shows that this relaxation time is less than 10 ps. Thus, the intrinsic response of the detector is expected to be less than 10 ps. Our experimental results are also included in Fig. 1. Better agreement between experiments and theory can be achieved by adjusting the constants in the formulation. We note that the sensitivity of the material increases as the temperature is decreased. The ratio $\Delta R/R$ changes by a factor of approximately 20 between 77 and 300 K. This is in agreement with our experimental results that we discuss in Section VI of this paper.

A quality measure of the detector that we will discuss in the next section is the amount of resistance change for a given amount of absorbed power. We will represent this measure by the symbol $F$, where

$$F = \Delta V/(P_0 \cdot I_b) = \Delta R/P_0 \ \Omega/\mathrm{W} \tag{14}$$

and,

- $F$ ohm change per watt absorbed,
- $\Delta V$ voltage change across the crystal,
- $P$ power absorbed by the sample,
- $I_b$ bias current through the sample.

We find experimentally that $F$ is approximately 0.03 Ω/W at 77 K for the detectors that we fabricated.

## III. Detector Fabrication

As depicted in Fig. 2, the Ge crystal is sandwiched between a coplaner transmission line and an oversized WR(28) waveguide. The size of the coplaner transmission line is chosen to insure a 50-Ω characteristic impedance up to the Ge crystal. When the coplaner transmission line is inserted into the waveguide, the resulting aperture has the dimensions of a WR(28) waveguide. The 50-Ω coplaner transmission line is used in the impedance measuring circuit which responds to hole mobility changes in the crystal. Connection to the coplaner transmission line is through the sides of the waveguide orthogonal to the electric fields. Experimentally, we have shown that the structure decouples the microwave frequencies from the low-frequency measuring circuit.

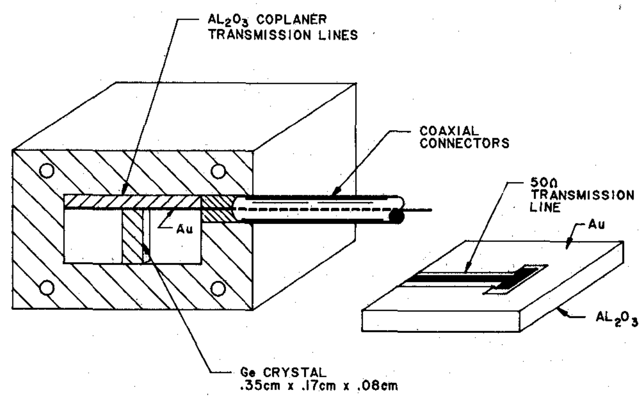

Fig. 2. Detector mount with transmission line.

We use p-type 17-Ω·cm Ge for our detectors. The dc resistance of the Ge crystal is calculated at various temperatures using the following equations.

### A. *Conductivity Relationship*

$$\sigma(T_l) = q\left(1.05 \times 10^9 T_l^{-2.33}\right) P(T_l). \tag{15}$$

### B. *Ionized Hole Concentration Calculation $P(T_l)$*

The ionized hole concentration in Ge does not vary much from room temperature to liquid nitrogen temperature and is approximately the acceptor concentration. This effect is caused by the small band gap.

### C. *Resistance Calculation*

$$R = L/tw\sigma(T_l). \tag{16}$$

Our crystal size is approximately $0.17 \times 0.35 \times 0.08$ cm. At room temperature, the crystal has a resistance of 442 Ω. The crystal has a resistivity of 17 Ω·cm. At 77 K, the resistance dropped to 25.9 Ω or a factor of 16.3 from room temperature. Equation (15) suggests that the resistance will change by a factor of 23.8 for a temperature change from 300 K to 77 K.

The thickness of our Ge crystal is approximately three skin depths at 35 GHz, as determined by the classical formula

$$t = 3 \times \mathrm{Im}\left\{ \omega^2 \mu\epsilon - j\omega\mu/\sigma \right\}^{-1/2}. \tag{17}$$

For 17-Ω·cm material with a dielectric constant of 16, three skin depths is approximately 0.07 cm. We used a crystal thickness of 0.08 cm in our detector. However, at high frequencies, we must also consider the effect of the carrier relaxation time. Mobility can be expressed in terms of a relaxation time by the following relationship:

$$\mu = q^2\tau/m. \tag{18}$$

For a mobility of 1800 $cm^2/v \cdot s$ and an effective mass of 0.3 $m_0$, we find that the relaxation time in Ge is approximately 0.3 ps at 300 K and 7 ps at 77 K. The phase $\omega\tau$ is approximately 0.065 rad at 300 K, 7.3 rad at 77 K, and 35 GHz, which says that the relaxation of the carriers affects the mobility at 77 K. A simple analysis of the effect is found in Kittel [8]. When the phase $\omega\tau$ is approximately one, Kittel shows that the conductivity becomes complex and is given by the following relationship for high frequencies:

$$\sigma = \sigma_0(1 + j\omega\tau)/(1 + (\omega\tau)^2). \tag{19}$$

A better determination of the penetration depth can be determined by substituting the complex conductivity into (17). Experimental evidence suggests that one effect of the complex conductivity at 35 GHz is to make the microwave penetration depth relatively independent of temperature. This is due to the fact that the real part of the conductance is stationary for different values of $\tau$, when $\omega\tau = 1$. Also, the imaginary part of the conductance is independent of $\tau$ for large $\omega\tau$.

Ohmic contacts were made by evaporating Au onto Ge in a vacuum system. The Au is evaporated on 0.35-thick Ge substrate. Next, the crystal is cut to size with a diamond saw. The resulting parallelepiped is then etched with seven parts of $NHO_3$, two parts of HF, and one part of red-fuming $NHO_3$. Tabs are then soldered onto the ends of the crystal. This structure is soldered onto the center conductor of the coplanar transmission line as depicted in Fig. 2.

## IV. Impedance Measuring Circuit

The impedance change of the Ge crystal was measured by biasing the crystal with a constant current and measuring the voltage change across the crystal caused by the absorption of microwave energy. The circuit for the biasing network is depicted in Fig. 3. The crystal is biased with a 100-$\mu$s bias pulse. This bias pulsewidth does not cause appreciable lattice heating for a 1-A bias. In fact, we have used millisecond 1-A bias pulses without appreciable lattice heating. A 100-ns microwave pulse is supplied by a 35-GHz magnetron which causes a potential change to occur across the crystal. One-half the voltage change then travels to the recording oscilloscope. The 100-$\Omega$ transmission-line lengths must be adjusted so that the reflected pulse from the bias pulse source does not interfere with the received signal at the oscilloscope.

We feel that the speed of the detector is limited by the capacitances at the transitions between the transmission lines. Our detector has a response time faster than 2 ns, which is the rise time of one of our sources.

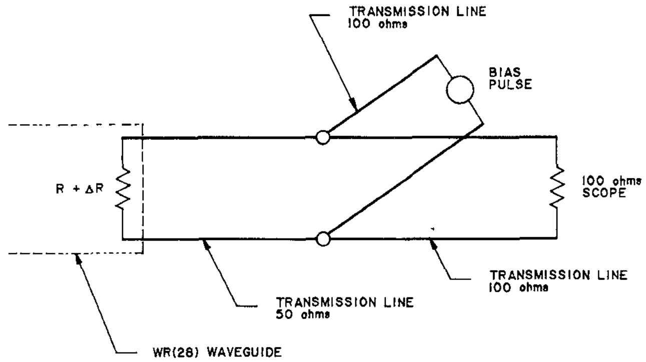


Fig. 3. Circuit diagram for resistance measurement.

## V. Circuit Model of the Hot-Carrier Detector

It is convenient to develop a circuit model of the crystal for matching purposes. This is done by using the following expression for current density:

$$J = \left(\frac{\sigma_0}{1 + j\omega\tau} + j\omega\epsilon\right)\tilde{E} \tag{20}$$

where $\tau$ is the relaxation time found in (18). A circuit model representing the detector is a resistance in series with an inductance shunted by a capacitance. The component values in the model are calculated from the equations

$$C = \epsilon A/l \tag{21}$$

$$R_0 = l/\sigma_0 A \tag{22}$$

$$L = R_0\tau. \tag{23}$$

$R_0C$ is the dielectric relaxation time of the crystal. At 35 GHz, we match the detector into the waveguide by tuning out the capacitance $C$. This is done by inductive iris apertures or three probe capacitance tuning screws.

## VI. Experimental Results

For discussion, we selected a detector whose measurements exhibited saturation effects. Fig. 4 represents the measured response of the detector under consideration. The response factor $F$ given by (14) increased from 0.008 to 0.03 from 300 K to 77 K. However, this much change was not observed in the other five detectors that were fabricated. In all cases, the detector measured output signals for input microwave pulses between 0.8 W and 10 kW at 77 K and 5 W and 10 kW at 300 K. The detector reflected more than 25 percent of the incident microwave energy. Thus, a properly matched detector can respond to less than 0.5-W pulses at 77 K.

Fig. 5 is a plot of output voltage versus bias current. The output saturates at 2.5 A and 0.55 A at 77 K and 300 K, respectively. It is our opinion that this saturation is due to the change in mobility at high fields or conductivity modulation caused by the injection of mobile carriers at the contacts.

Analysis of a transmission line connected to an oscilloscope shows that a time-varying ohmic termination with

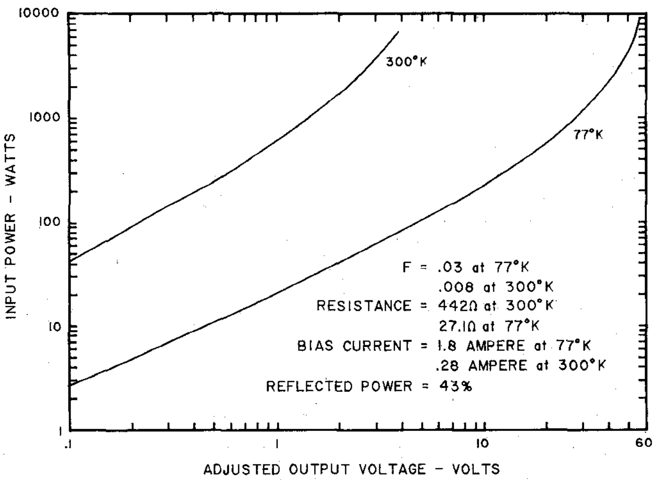


Fig. 4. Measured detector response.

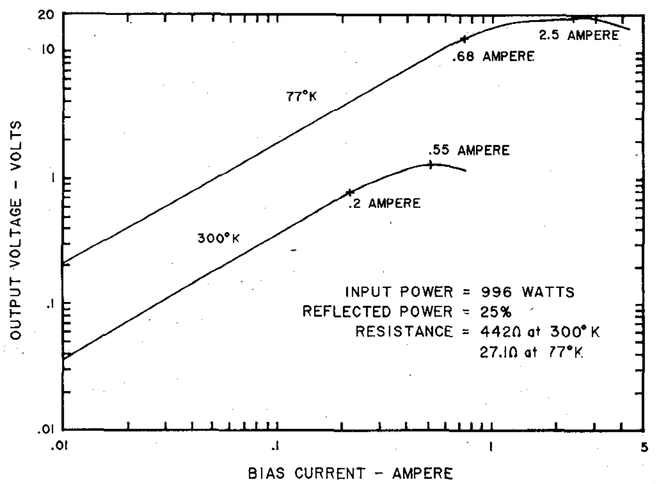


Fig. 5. Output voltage versus bias current.

a bias current passing through it causes a voltage pulse to appear across the scope. The result of this analysis is given by

$$V = IR\Delta R/(Z_0 + R + \Delta R). \quad (24)$$

Note that the voltage pulse becomes independent of resistance change for changes larger than the $Z_0 + R$, where $Z_0$ is the characteristic impedance of the transmission line and $R$ is the initial resistance of the crystal. We believe that the saturation observed at 77 K for input power levels larger than 1000 W, as depicted in Fig. 4, is caused by $\Delta R$ increasing beyond $Z_0 + R$.

We have also observed that the voltage reflectivity from the Ge crystal inserted into the waveguide is almost temperature independent. As previously pointed out, $1/\omega$ is approximately 4.55 ps at 35 GHz, and we expect that the mean free time to scatter will vary from 0.3 to 7.3 ps from 300 K to 77 K, respectively. At 4.55 ps, we are at a stationary point in the mobility frequency relationship expressed by (19) where $\omega\tau = 1$. Thus, we expect and we have observed that the reflectivity of the Ge crystal in the waveguide varies approximately 20 percent as the temperature is changed from 77 to 300 K at 35 GHz.

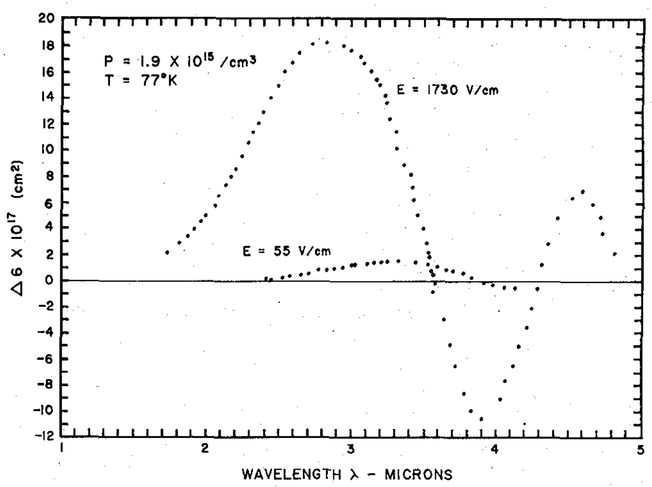


Fig. 6. Optical absorption cross section versus Wavelength.

## VII. Summary

Bulk Ge microwave detectors have been built and used in experiments. Our detectors respond to microwave pulses between 0.5 W and 10 kW. The rise time of the detectors is believed to be limited by the external circuitry. The intrinsic response time of these detectors is less than 10 ps. This number is based on the facts that the energy relaxation of the holes interacting with the phonons is less than 10 ps and the momentum relaxation time is an order of magnitude less [6]. Our detectors operate between 22 and 40 GHz in WR(28) waveguide. At lower frequencies, these detectors can be fabricated in coaxial transmission lines. However, appropriate care must be taken to prevent voltage breakdown. The detector responds to power absorbed per carrier. We believe that micromachined detectors will be able to detect power levels considerably below 0.5 W. However, we have not determined the lowest detectable power level.

There are other potential hot-carrier interactions which we believe can be used to fabricate microwave detectors or transducers. Pinson and Bray [4] have experimentally shown that the optical absorption cross section in the 2–4-$\mu$m region changes considerably with applied electric field. The effect is due to intervalent band absorption of optical energy. The relaxation time for this process is less than 10 ps for p-type Ge. Experimental variation in absorption cross section from Pinson and Bray [4] is given in Fig. 6. It is our opinion that we can build microwave to optical transducers using this effect to detect 1–100-kW microwave pulses with nanosecond rise times. Other materials such as AlSb may exhibit the same effect near 1.3 $\mu$m. At 1.3 $\mu$m, we can use fiber optics. We are proposing to study this effect to determine the feasibility of building a microwave to optical transducer.

## VIII. Acknowledgment

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