A MICROWAVE-TO-OPTICAL TRANSDUCER*

L. F. Jelsma

University of California
Lawrence Livermore National Laboratory
Livermore, California 94550

ABSTRACT

My theoretical predictions and initial experimental results show that intravalent absorption in semiconductors can be used to modulate light with electric fields that vary at 35 GHz. To produce electric fields of 50–1000 V/cm in a WR(28) waveguide, I use a microwave source that generates a 10- to 160-kW pulse lasting 100-ns. With this source, I can modulate more than 16% of the 3.39-μm light from a HeNe laser at 77 °K and more than 8% at 300 °K. The percentage of modulation is better than expected.

In this paper I develop the light modulation theory, present my initial experimental results, and speculate on how to build a practical microwave-to-optical transducer. I also point out that the transducer, fabricated from germanium, can be used to create fast rise-time optical pulses in the 2- to 4-μm region of the spectrum.

INTRODUCTION

Optical systems used in the control and diagnosis of high-power microwave sources, lasers, and plasma–fusion systems require transducers that can transform large electric fields (>50 V/cm) between 0 and 100 GHz into modulated light signals. In an outstanding experiment, Pinson and Bray (1) demonstrated that when one applies an electric field larger than 50 V/cm to a germanium crystal, the shift in carrier distribution in the heavy-hole band changes the absorption of infrared radiation passing through the crystal. Their results show that one can use this effect to measure rapidly changing electric fields between 50 and 2000 V/cm. Based on bulk avalanche breakdown limits, the largest field that this type of transducer can measure is 250,000 V/cm.

To my knowledge, the Pinson and Bray experiment is the only attempt to measure the change in the carrier distribution of a semiconductor that is in the presence of an electric field. In their experiment, they created a shift in carrier distribution, or the distribution of holes, by applying a step voltage across a piece of germanium at 77 °K. The result was a measurable change in the intravalent band absorption of light between 2 and 4.5 μm. The relaxation time of this process was below 4 ps. I will show that the relaxation time at 300 °K is below 1 ps. This implies that one can build a transducer that responds to a 1 ps-time change in the electric field of a germanium crystal at a lattice temperature of 300 °K. It also implies that it is possible to build a microwave-to-optical modulator or field-to-optical transducer (2).

In this paper I describe a microwave-to-optical transducer in which electric fields change the intraband absorption of light in a semiconductor. I develop a theoretical model for the transducer and discuss the results of the transducer experiment.

THEORETICAL CONSIDERATIONS FOR A MICROWAVE-TO-OPTICAL TRANSDUCER

In Fig. 1 we see that a semiconductor has three basic valence bands. The low-energy band is the heavy-hole band. The next highest energy band is the light-hole band. The third band is separated from the heavy-hole band at zero momentum by a spin orbital splitting of 0.29 eV.

At 77 and 300 °K, the majority of the holes are in the heavy-hole band and have a quasi-equilibrium Maxwellian distribution, as indicated in Eq. (1):

$$f_0(\epsilon T_p) = \frac{2\sqrt{\epsilon}}{(\pi K T_p/Q)^{3/2}} \exp\left(\frac{-\epsilon}{KT_p/Q}\right), \tag{1}$$

where T_p is the hole temperature (in °K), ϵ is the kinetic energy of holes in the crystal (in eV), and Q is the electron charge. The distribution is normalized to one carrier.

My numerical model is a self-consistent formulation. I use it to solve Boltzmann's equation and to satisfy an energy flow equation describing the energy flow between the holes and the phonons in the lattice. To satisfy both equations, I make the hole temperature in Eq. (1) a function of the applied electric field. I use the term quasi-equilibrium distribution to imply that the hole temperature in Eq. (1) is field dependent in the numerical model.

Equation (2) is a modified Boltzmann distribution for the application of an electric field to a germanium crystal, and Eq. (3) is an energy balance equation.

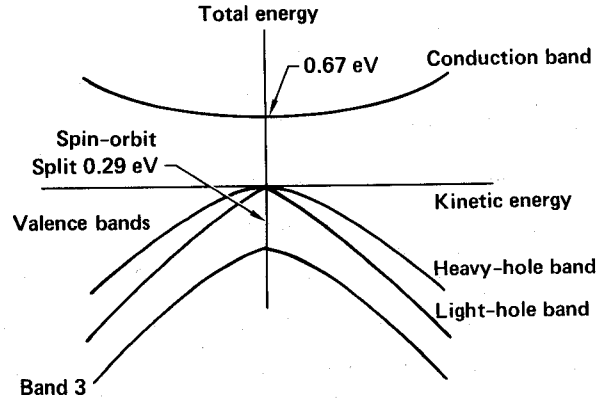

Figure 1. Spin-orbit split of the valence band for germanium.

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$$f(\epsilon,T_p,T_L) = f_0(\epsilon,T_p)\left\{1 - \left[\frac{[QE(t)\,\tau(\epsilon,T_p,T_L)]^2}{mKT_p}\right]\left[1 - \frac{2\epsilon}{3KT_p/Q}\right]\right\}, \quad (2)$$

$$\frac{\int_0^\infty \epsilon f_0(\epsilon,T_p)\,\tau(\epsilon,T_pT_L)d\epsilon}{3KT_p/2Q}\,\frac{[QE(t)]^2}{Qm} + \left(\frac{d\epsilon}{dt}\right)_{ac} + \left(\frac{d\epsilon}{dt}\right)_{0p} = 0\,, \quad (3)$$

where T_L = the lattice temperature in °K, $E(t)$ = the electric field in V/m, and m = the effective mass of the hole/kg.

The Boltzmann distribution is justified by the following argument:

$N(p)\,(3kT_p/2)$ = the average amount of energy in momentum state p, (4)

$N_0(p)\,(3kT_p/2)$ = the quasi-equilibrium energy in momentum state p, (5)

$QE\tau(p)$ = the average momentum given up to holes from the electric field that are scattered with momentum state p, (6)

$[QE\tau(p)]^2/3mKT_p$ = fractional amount of quasi-equilibrium energy that can be scattered into or out of momentum state p. (7)

$p^2/2m$ = the amount of energy that a hole has in momentum state p. (8)

The energy balance equation

$$N(p)\,(3kT_p/2) = N(p)\,(3kT_p/2) - N(p) \times \left[(QE\tau(p))/2m\,(3kT_p/2)\right]\left[(3kT_p/2) - (p^2/2m)\right]. \quad (9)$$

is Eq. (2). I originally derived the modified Boltzmann function by using an iterative solution to Boltzmann's equation.

In Eq. (2) the quasi-stationary Boltzmann distribution is expressed in terms of lattice temperature, hole temperature, relaxation time, and the the kinetic energy of the holes in the lattice. In my computer model, I use expressions for relaxation time found in Pinson and Bray (1). I use an expression developed by Dingle (3) for the effects of impurity scattering. Equation (3) functions represent the power absorbed by the acoustical and optical phonon fields. For these functions I use an expression developed by Conwell (4).

RESULTS OF THE COMPUTER ANALYSIS

Figure 2 depicts the hole-scattering time in 2 Ω/cm of germanium at three different temperatures. It is a plot of the inverse of the sum of the relaxation frequencies derived by Pinson and Bray (1) and Dingle (3). The rapid falloff in relaxation time at high kinetic energies is the result of stimulated emission of optical phonons. At the low end of the energy scale, the falloff is the result of impurity scattering. Impurity scattering affects the relaxation time at long wavelengths. The hole relaxation time is a measure of the time that it takes the holes to relax and go back to an equilibrium state. Thus, the speed at which this system can modulate light is limited by the relaxation time. As I pointed out before, the hole relaxation time does not increase beyond 1 ps at 300 °K.

Figure 3 is a plot of the difference between Eq. (2) and the equilibrium distribution for a 2-Ω/cm material. It is normalized to one carrier per electron volt, and is for different applied electric fields, each of which has a lattice temperature of 300 °K. For convenience, I have calibrated the x axis in wavelengths. If I want the curve to represent density, I must relabel the x-axis in terms energy in electron volts. This implies that I have not multiplied Eq. (2) by the Jacobian determinant to transform energy to wavelength.

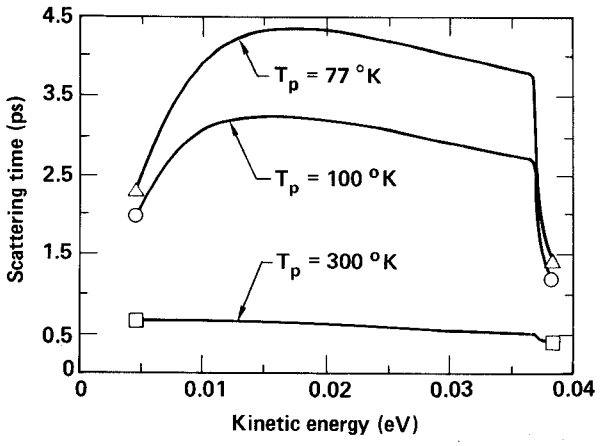

Figure 2. Hole-scattering time in 2-Ω/cm germanium at three different temperatures.

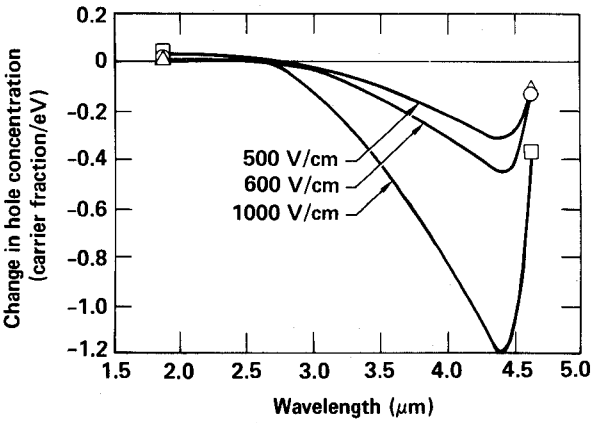

Figure 3. Change in hole concentration in 2-Ω/cm p-type germanium for different fields and wavelengths at 300 °K.

The change in optical absorption is directly proportional to the change in hole concentration. To use this system in an optical modulator, I suggest using about a 4.3-μm light source for the maximum index of modulation. In my experiment, I used a 3.39-μm laser.

Figure 4 depicts the change in hole concentration as a fraction of one carrier per electron volt for different applied electric fields at 77 °K. In Figs. 3 and 4, the minimum change in hole concentration at long wavelengths is caused by the impurity scattering term in the expression for net scattering frequency. Eliminating impurity scattering causes the change to decrease beyond the minimum. At short wavelengths, the rapid change is caused by the stimulated emission of phonons. In Eq. (2), the crossover in the change in hole concentration is inversely proportional to the hole temperature. The crossover approaches the short wavelength part of the spectrum as the electric field increases; thus, the hole temperature increases as the applied electric field increases. This effect was verified by Pinson and Bray's experiment (1). In my formulation, the hole temperature is obtained from Eq. (3).

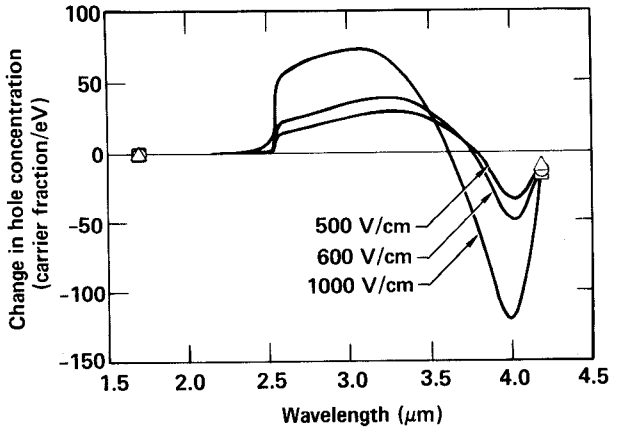

Figure 4. Change in hole concentration and per hole kinetic energy vs wavelength for 2-Ω/cm p-type germanium at 77 °K.

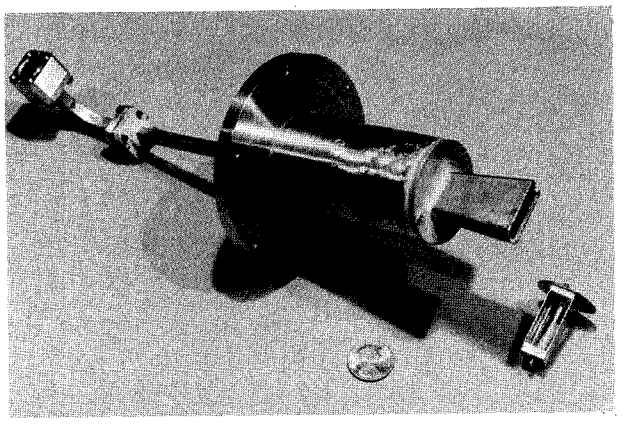

Figure 5. Microwave-to-optical transducer.

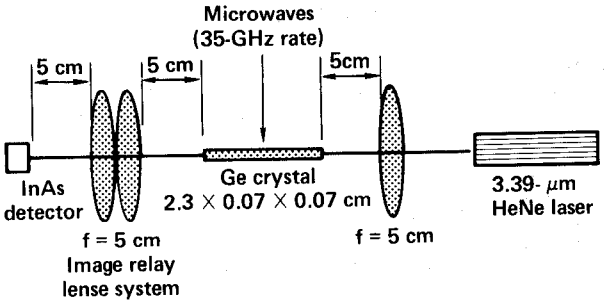

Figure 6. Optical system used in the experiment.

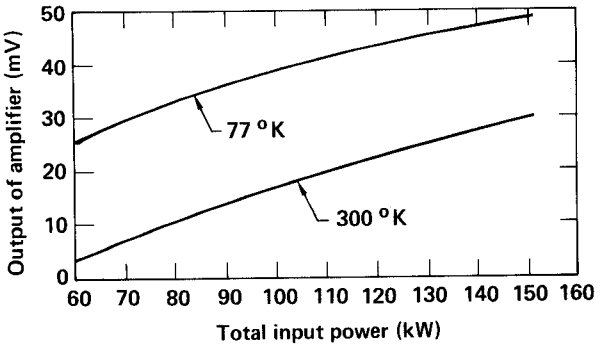

Figure 7. Experimental results: InAs detector output voltage vs total input power.

FABRICATION OF THE TRANSDUCER

To make the transducer, we place a 2.3- × 0.07- × 0.07-cm piece of 2-Ω/cm germanium crystal at the open end of a WR(28) waveguide. All surfaces of the crystal are optically flat. The polished crystal, which has a dielectric constant of 16, is a good optical waveguide. The microwave waveguide is stretched toward the electric field, in the b direction.

Figure 5 shows the stretched waveguide extending through a stainless-steel durer (for cooling) and the holder containing the crystal. The holder is at the end of the microwave waveguide. In this arrangement, light travels in a direction orthogonal to the microwave signal. At the same instant, the microwave pulse illuminates the whole crystal surface on one side. The light travels down the crystal in 192 ps, limiting the time response of the detector. To achieve a response time near 1 ps at room temperature, the microwave signal must travel along the crystal in the direction of the light.

EXPERIMENTAL RESULTS

Figure 6 shows the optical system used in the modulator experiment. The output of the laser was focused onto the end of the germanium crystal, which guided the light. The output image was then relayed onto an InAs detector that had a rise time of approximately 200 ns. The output light was modulated with a 35-GHz source by a square 200-ns pulse. The resulting output signal from the detector had a triangular wave shape, implying that the detector integrated the modulation waveform.

Figure 7 shows the output of the amplifier connected an oscilloscope after the GaP optical detector. The gain of the amplifier was approximately 10. At liquid nitrogen temperature, the output increases by a factor of approximately 5. The wavelength of the HeNe laser was 3.39 μm. I feel that, based on my theory, the modulation can be increased by changing the wavelength to approximately 4 μm.

In the laser I observed transverse modes of oscillation. This caused considerable noise in the detected optical signal. Fortunately, the detector response reduced the noise so that I could measure the modulation.

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