

Interaction of Microwave Biased n-GaAs and 337 μm Radiation

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Abstract—n-GaAs cooled to 4.2 K is impact ionized with X-band microwave pulses. Fast rise-time modulation of 337 μm radiation is observed. The GaAs is less absorptive in the ionized state than in the un-ionized state.

INTRODUCTION

THE development of submillimeter devices has received considerable interest in recent years [1]–[8]. The availability of various types of modulators in the submillimeter region has remained limited, however. The simplest one, the mechanical chopper, is restricted to square wave or rectangular pulses and low modulation rates. Stark modulation can be used with waveguide laser sources for combined frequency and amplitude modulation. The modulation characteristics, however, are specific to the individual lasing transition [4]. Free carrier absorption in cooled, impact ionized Ge has been reported over most of the submillimeter region. The observed bandwidth is 100 MHz [5]. In this paper, we report details of a fast GaAs impact ionization modulator for submillimeter radiation. A distinctive feature of our device is that ionization increases the submillimeter transmission, in contrast to the Ge absorption modulator.

The interaction of high-purity n-GaAs with submillimeter radiation has been used previously to make fast, sensitive detectors for the 100 μm –350 μm region [6]–[8]. These devices are operated at liquid helium temperatures. Light is absorbed when the photons ionize electrons frozen out at donor sites. The electrons can be treated as occupying modified hydrogenic bound states, where the usual hydrogen energy levels given by $E_n = -e^4 m / 8 \hbar^2 \epsilon_0 n^2$ must be corrected for the effective mass and dielectric constant of GaAs. The resultant energy difference between the ground and first excited states is $E_2 - E_1 = 4.34$ meV, corresponding to a photon of $\lambda = 282$ μm . This bound state excitation has been found to dominate the submillimeter absorption in GaAs for low excitation levels. The observed photoconductive response results from the subsequent thermal ionization of the excited electrons into the conduction band [9], [10].

When an electric field of 1.6 V/cm is applied to the material, impact ionization of the electrons begins, and avalanche break-

down occurs at about 6.6 V/cm [11]. Once the electrons are excited out of the impurity ground state, they are unable to absorb submillimeter radiation by the mechanism described above. For GaAs at 4.2 K, free carrier absorption is not significant for the excitation levels used, and the transmission of light through the GaAs increases. This effect is the basis for the modulation reported below.

To impact ionize our device, we use a microwave signal. The usual method for initiating avalanche breakdown is to apply an electrical pulse directly to the device. Circuit considerations, however, limit the bandwidth that can be achieved with this method. By placing the modulator at the end of a waveguide or in a microwave cavity, much wider bandwidths can be theoretically achieved. With this modulation method, and a sufficiently fast submillimeter detector, the carrier ionization and recombination times could be accurately measured by observing the modulation rise and fall times.

EXPERIMENTAL CONFIGURATION

The experimental arrangement used to study the modulator characteristics is shown in Fig. 1. The microwave bias is supplied by a klystron followed by a TWT amplifier. The klystron is modulated by a fast-rise-time pulse generator. The microwave power incident on the GaAs is controlled by a precision attenuator, and both the incident and reflected power are measured. Optimization of the microwave coupling to the modulator can be achieved with a slide screw tuner. The modulator is a piece of high-purity epitaxial n-GaAs grown on an insulating substrate. (The material was obtained from Cayuga a Narda Subsidiary). The epilayer is 100 μm thick, with donor and acceptor concentrations of $N_D = 4.61 \times 10^{14}$ cm^{-3} and $N_A = 2.45 \times 10^{14}$ cm^{-3} , respectively. The device is mounted on a quarter-wavelength polyethylene support at the end of a waveguide which is at the bottom of a liquid helium [Dewar (Fig. 2a)].

An HCN gas discharge laser with about 10 mW of output power at 337 μm is used as a convenient submillimeter source. The submillimeter beam is focused into a $\frac{1}{2}$ -in-diam stainless steel light pipe to an optical switch that directs the light either to a calibrated thermopile or to a $\frac{1}{8}$ -in-diam hole that couples into the microwave waveguide which contains the modulator. The bottom end of the waveguide has another $\frac{1}{8}$ -in-diam hole through which the modulated light passes to a detector. The detector is also made from GaAs and is used in the dc-biased

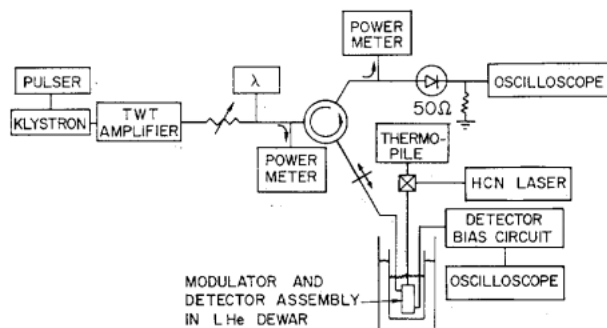


Fig. 1. Experimental configuration for the microwave biased GaAs modulator.

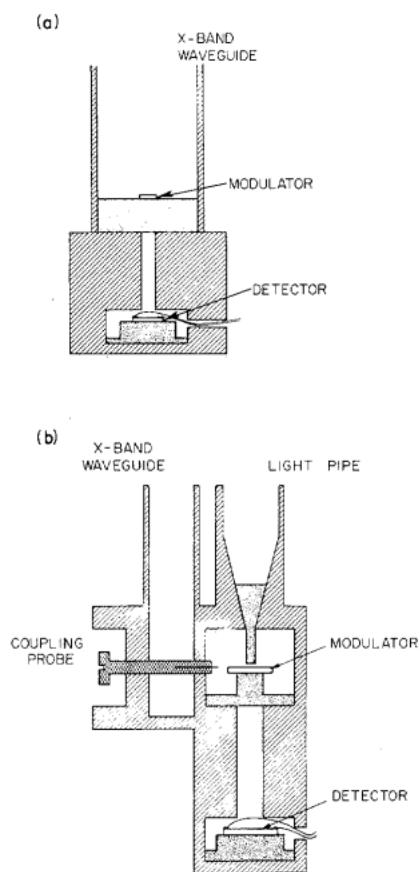


Fig. 2. Details of modulator and detector assembly for (a) terminated waveguide and (b) microwave cavity.

photoconductive mode. The submillimeter coupling hole is made long enough to prevent leakage of the evanescent X -band signal used as the modulating signal.

A second configuration, shown in Fig. 2(b), is also used. Here, the modulator is placed in a microwave cavity which is coupled to the waveguide by an adjustable probe. The submillimeter radiation is directed separately through a light pipe to a combined metal and dielectric cone that concentrates the radiation directly on the modulator. The bottom of the cavity has a $\frac{1}{4}$ -in-diam hole through which the light passes to reach the detector. While the modulation index is smaller in this configuration, a larger signal amplitude results from the im-

proved coupling of the light to the modulator and detector assembly.

The detector is connected by a coaxial cable to a dc bias circuit outside the Dewar. Provision is included for changing the load resistance to optimize the detector performance (Fig. 3). The detector signal is observed on an oscilloscope.

EXPERIMENTAL RESULTS

The modulation characteristic of our device has been studied as a function of microwave power and of pulsewidth. As the incident microwave power increases, the reflected microwave power decreases abruptly, indicating the onset of impact ionization. Beyond this point, the free carrier concentration changes smoothly with increasing power, and the slide screw tuner must be adjusted for each power level to optimize the coupling between the microwave source and the modulator. The modulation signal appears as an increased submillimeter transmission (Fig. 4), peaking at a modulation index of 30 percent, and then beginning to drop at the maximum available microwave power (Fig. 5).

The waveform displays pronounced departures from the rectangular microwave bias pulse (Fig. 6). Just above the impact ionization threshold, the modulation takes several microseconds to achieve full modulation. As the bias power increases, the signal undergoes a series of instabilities during part or all of the microwave pulse. These instabilities are also a function of the incident submillimeter power. The variations can be observed on the reflected microwave power as well as on the transmitted submillimeter signal. Of particular note are those levels where a pulse-to-pulse coherent oscillation occurs with a 10–15 μ s period. Based on our device dimensions and low-field mobility, this period corresponds to the electron transit time for fields of about 2.5 V/cm. While this value is comparable to the fields required for impact ionization, no explanation can be advanced for the appearance and disappearance of the oscillations.

Using increasingly shorter pulses, the rise time is measured to be less than 150 ns. It is found that the rise time of the microwave biasing system used is less than 70 ns. The limiting factor on the measured rise time is the dc-biased detection scheme. With the 3 M Ω load resistor (optimum responsivity load), the rise time of the system is greater than 1 ms. By reducing the load resistor to 100 Ω , the rise time could be lowered to 150 ns. Further reduction of the load resistor reduced the responsivity of the detector sufficiently that signal-to-noise problems prevented further observations. Thus the absolute rise time of the modulation could not be determined with our experimental arrangement.

The modulation index is believed to be a function of the number of electrons frozen out on donor impurities or excited to the conduction band rather than of the applied electric field. An experimental check is done wherein the modulator is replaced by another piece of the same material with electrical contacts applied. This piece of GaAs is heated and its relative transmission is measured as a function of resistance. Over the temperature range covered, 4.2 K to about 6 K, the mobility is almost constant and the resistance is thus a good measure of the relative carrier concentration. From the observed trans-

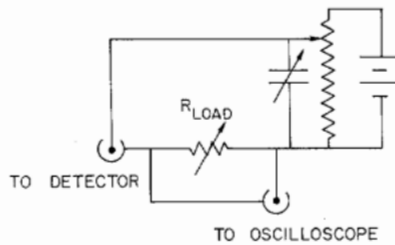
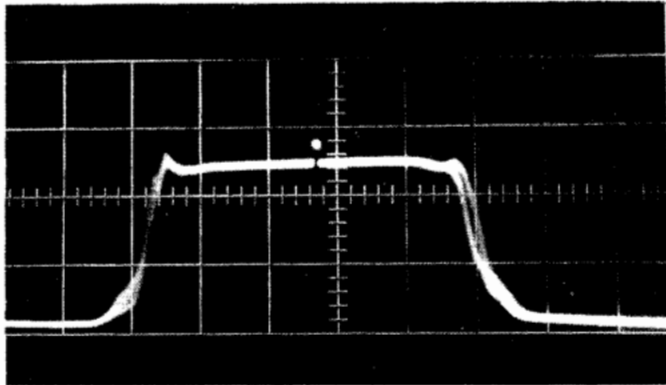
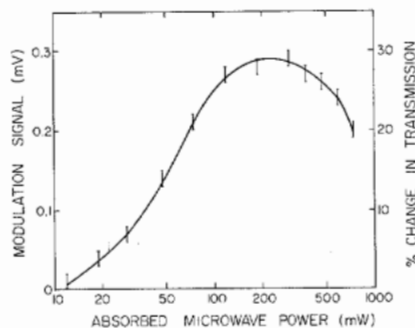


Fig. 3. GaAs detector dc bias circuit.

Fig. 4. Detector output for combined microwave modulated and mechanically chopped submillimeter radiation. The increased transmission can be seen as the small spike on top of the rectangular pulse from the chopper. Vertical scale: 200 mV/div. Horizontal scale: 200 $\mu\text{s}/\text{div}$.Fig. 5. Modulation signal as a function of absorbed microwave power. Bias pulse width is 1 μs , repetition rate is 1 kHz, and incident submillimeter power is 2.5 mW.

mission change, it appears that a rather small change in the number of free carriers can lead to the modulation index quoted above (Fig. 7). Apparently the impact ionization excites only a small fraction of the donors. Complete breakdown should increase the carrier concentration by about 5 orders of magnitude [12], [13].

DISCUSSION

An understanding of the modulation index requires a knowledge of the interaction of submillimeter light with the frozen out impurity ground state and with the free carriers produced by impact ionization. The absorption cross section for impurities can be determined from the responsivity of the material when used as a dc-biased detector. For a given submillimeter

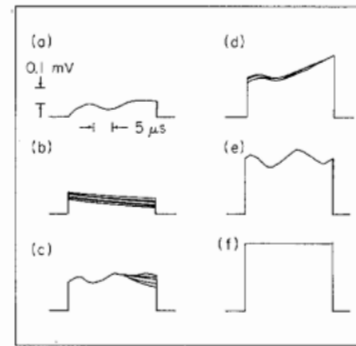
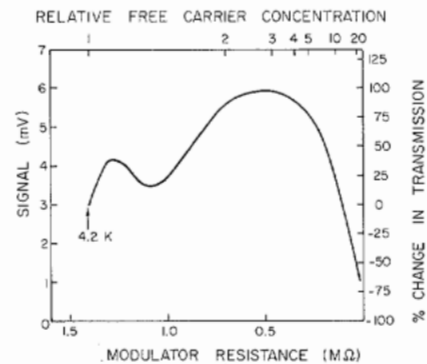
Fig. 6. Modulation signal as a function of time for absorbed microwave power of (a) 12 mW, (b) 15 mW, (c) 31 mW, (d) 58 mW, (e) 101 mW, and (f) 162 mW. Bias pulsewidth is 23 μs , repetition rate is 3.2 kHz, and incident submillimeter power is 1 mW.

Fig. 7. Dependence of modulator transmission on free carrier concentration relative to 4.2 K thermal equilibrium values. The carrier concentration was increased by directly heating the sample.

intensity, there will be a change in the free carrier concentration which will manifest itself as a change in detector current. Knowing the impurity concentration and the incident submillimeter power, and using a reasonable estimate for the excited carrier lifetime, the number of absorptions per unit time can be derived. Based on a lifetime of 5 ns [6], the cross section for our material is calculated to be at least $1.5 \times 10^{-13} \text{ cm}^2$, corresponding to transmission of 67 percent of the light. In fact, the doubling of the transmission seen in the thermal data indicates that the calculated cross section is somewhat low.

For free carriers, the usual expression for the short wavelength absorption coefficient can be slightly modified to generate an expression for the cross section, $\sigma = \lambda^2 e^3 / 4\pi^2 \epsilon_0 m^{*2} \cdot c^3 \mu \sqrt{\epsilon_r}$ [14]. From measurements of the material resistance we infer a 4.2 K mobility of $\mu = 4 \times 10^4 \text{ cm}^2/\text{V} \cdot \text{s}$, in good agreement with reported values for comparable material [13]. The dielectric constant is taken to be 11.5 [15] and the effective mass $0.0665m_0$ [16], giving a free carrier absorption cross section of $9.9 \times 10^{-15} \text{ cm}^2$. This value is an order of magnitude less than the impurity cross section, indicating that as electrons are excited from the bound states to the conduction band, the transmission should increase as observed. This simple theory fails to account for the decrease in modulation index at the microwave bias power limit, nor does it explain the change from transmission to absorption observed in the thermal data.

The rise time of the modulation effect has been measured as less than 150 ns, limited by the submillimeter detection circuit. The reported recombination time for GaAs photoconductive detectors is about 5 ns [6] and depends on the density of compensated impurities. This detection limit could be realized by using a cryogenic preamplifier [17] or by employing a microwave biased detection system [8]. Other possible detectors include MOM tunnel diodes [18] and Schottky barrier diodes [19]. These faster detectors should allow utilization of the full modulator bandwidth, which is expected to be defined by the same 5 ns free carrier recombination time mentioned above for photoconductive detectors.

Microwave biased modulation allows the relatively high GaAs resistance to be transformed down to a low microwave impedance, substantially reducing the RC time constant encountered in the usual dc-biased breakdown system. In addition, the power dissipated in the GaAs is typically 200 mW, an order of magnitude less than that dissipated in the Ge impact ionization modulator [5]. This results in a substantially reduced heat load on the cryogenic system employed and would have important applications in any practical system.

In conclusion, high-purity epitaxial GaAs, cooled to liquid helium temperatures, is impact ionized with pulsed microwave radiation. The transmission of 337 μm light through the GaAs increases by as much as 30 percent during application of the microwave pulse. Thermal data indicate that a doubling of the transmission should be possible with higher microwave power. Alternatively, a thicker epilayer should absorb all of the incident light, allowing transmission of submillimeter light only when biased above breakdown. Applications of the resultant submillimeter pulses include high-repetition-rate pulse code modulation of submillimeter radiation, fast rise time pulses for thermonuclear plasma diagnostics [20], and pulsed submillimeter radar.

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