LA-UR -81-2882

CONF - 811207--2

TITLE: SUB-100 ps BULK-RECOMBINATION-LIMITED InP:Fe PHOTOCONDUCTIVE DETECTOR

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SUBMITTED TO: International Electron Devices Meeting, Washington, D. C.,
December 8-10, 1981

MASTER

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SUB-100 ps BULK-RECOMBINATION-LIMITED InP:Fe PHOTOCONDUCTIVE DETECTOR

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ABSTRACT

We have studied both surface and bulk excited semi-insulating InP optoelectronic switches. We have found that transient recombination in these devices is the same for both types of excitation. We conclude that the recombination is a bulk controlled process.

INTRODUCTION

Recently, considerable work has been done utilizing photoconductivity in semiconductors for high-voltage switching and radiation detection in the picosecond time domain. High-resistivity Si⁽¹⁾, GaAs⁽²⁾, InP⁽³⁾, GaP⁽⁴⁾, and CdSe⁽⁵⁾ have been studied. Short carrier recombination lifetime, high carrier drift velocity, and high resistivity are desirable materials properties for these applications. Intrinsic, single crystal semiconductors can have high resistivity ($\sim 10^8 \Omega\text{-cm}$), high electron drift velocity ($> 10^7 \text{ cm/s}$), and short carrier recombination lifetime ($\sim 10^{-9} \text{ s}$). Auston and coworkers have used amorphous⁽⁶⁾ and radiation damaged⁽⁷⁾ Si to achieve very short lifetimes, 4 ps and 8 ps, respectively. In doing this they have sacrificed the large single crystal carrier drift velocity, decreasing efficiency for optoelectronic switching and sensitivity for radiation detection. Fast recombination ($\sim 50 \text{ ps}$) with high drift velocity has been reported for surface-excited, semi-insulating GaAs⁽⁸⁾ and InP⁽³⁾ devices, but the mechanism for this recombination has not been identified. Moyer and coworkers⁽⁹⁾ have shown by magnetophotconductivity measurements that fast recombination in GaAs devices is probably surface controlled.

In this paper we report measurements of transient recombination in bulk-excited, semi-insulating InP optoelectronic switches. Several radiation sources with pulse durations less than 100 ps were used for this study. Our results show a transient recombination in InP:Fe of $< 100 \text{ ps}$. This fast recombination is seen in both surface and bulk excited devices. It is seen in material with high resistivity ($> 10^7 \Omega\text{-cm}$) and high carrier drift velocity ($> 10^7 \text{ cm/s}$).

DEVICE FABRICATION

The devices for this study were fabricated from Fe-doped, semi-insulating InP obtained from Crystalline Comm, Inc. The resistivity and electron mobility in this material were claimed by the manufacturer to be $2 \times 10^7 \Omega\text{-cm}$ and $2200 \text{ cm}^2/\text{V-s}$, respectively. The material was cut into pieces $0.5 \times 2.4 \times 5.0 \text{ mm}^3$ and polished in Br-methanol solution to remove surface damage. AuZn or AuGe ohmic contacts were evaporated and annealed briefly at 450°C with contact spacings of 1 mm. The active area of the devices was $1 \times 2.4 \text{ mm}^2$. The capacitance of these devices was measured to be 0.034 pF at 5 GHz on a network analyzer. The devices were mounted into microstrip housings using a conductive silver paint. Transition from microstrip to coaxial geometry was made with SMA connectors. During tests, one side of the device was biased and the opposite end (signal end) was connected directly into a sampling oscilloscope head. The response of the sampling system was approximately 40 ps.

CALCULATED DETECTOR RESPONSE

The peak current response of a photoconductor to an impulse of radiation (ignoring contact effects) in the charge-line configuration of this experiment is:

$$I = qv_d E/Sw$$

where: I = observed peak current
 q = electronic charge
 v_d = electron drift velocity
 E = energy deposited into detector by incident radiation
 S = contact spacing
 w = energy to create an electron-hole pair

We have ignored the current due to free holes because these have a much lower drift velocity than free electrons in InP. This formula also assumes that the incident radiation pulse duration is much shorter than the carrier recombination time in the device. Finally, it assumes that the impedance of the device is always much greater than that of the load, 50 Ω .

For optical illumination the energy to create an electron-hole pair is just the photon energy. For more energetic radiation this number has not to our knowledge been measured in InP. InP may be expected to be similar to GaAs, however, where w is approximately 5 eV. The electron drift velocity in InP in the low field regime may be calculated from the mobility. The energy deposited in the detector material may be calculated from the known reflectivity and absorption combined with a knowledge of the incident radiation energy.

MEASURED RESPONSE

The transient response of these devices was measured from several radiation sources: 6.5 MeV, 50 ps, electron beam pulses with beam currents from 15 to 150 μ A; 18 MeV, 30 ps, end-point Bremsstrahlung pulses of $\sim 10^8$ rads/s; 820 nm, 90 ps, ~ 0.3 W injection laser diode pulses; and 15 ps, 600 nm, ~ 50 W dye laser pulses. Figure 1 shows averaged sampling oscilloscope traces from the four radiation sources described. The risetime of the signal in each case is determined by the length of the excitation pulse and the response of the sampling system since the RC

response of the detector in the 50 Ω geometry is 3.3 ps. The falltime, however, shows effects due to the intrinsic detector response. There are also reflections present due to impedance mismatch in going from the detector to microstrip and in the transition from microstrip to coaxial. Some broadening in the primary response transient is probably due to these reflections. Data in Fig. 1(A), (C), and (D), were all taken with the device described previously. Data in Fig. 1(B), however, were taken on a device 12 mm in length rather than 5 mm. This moved the transition from device to microstrip out by 3.5 mm; and thus moved the reflection from that impedance mismatch further out in the decay transient. Because of this the shoulder of 1(A) becomes more clearly defined and occurs later in 1(B). For each case in Fig. 1 the intrinsic detector response is shown to be < 100 ps.

For two of the radiation sources we made an effort to determine quantitatively the sensitivity of the detectors. We estimate 8% absorption for 6.5 MeV electrons in a 0.5 mm thickness of InP. For a 150 μ A, 50 ps pulse this yields a deposited energy of 3.9×10^{-9} J. The measured peak current response of 55 mA with a bias voltage of 500 V may then be used to estimate electron mobility in the detector:

$$\text{mobility} = S^2 w I / V_{\text{app}} E$$

Assuming $w = 5$ eV gives an electron mobility of 1410 $\text{cm}^2/\text{V}\cdot\text{s}$. For 820 nm, 90 ps, 1 W illumination with a Q-switched, heterojunction GaAlAs/GaAs injection laser diode, we get an incident pulse energy of 0.09×10^{-9} J. We observed a peak current of 2 mA with an applied voltage of 233 V. Assuming one electron per incident photon and 30% reflection, we estimate the electron mobility to be 2057 $\text{cm}^2/\text{V}\cdot\text{s}$.

Both of these estimates of the electron mobility are close to the 2200 $\text{cm}^2/\text{V}\cdot\text{s}$ claimed by the manufacturer for the crystal. The variations are consistent with inaccuracies in our estimates of the actual pulse energies incident on the active region of the device and the uncertainty in w . These results indicate that the devices operate near 100% quantum efficiency for both surface and bulk excitation.

In addition to the measurements noted thus far, we have also measured the response of these devices to 1.06 μm and 337 nm laser pulses. Transient response to these sources is again <100 ps. Sensitivity to 1.06 μm light is low, however, due to the very low absorption coefficient for InP at this wavelength. Finally, we should mention that in the bulk excitation measurements we observed a long-lived tail in the response. The tail had a nonexponential decay over tens of nanoseconds and was 0.5 to 2% of the peak current in amplitude. This may be due to long-lived holes.

CONCLUSIONS

We have demonstrated that sub-100 ps response in InP:Fe optoelectronic switches is controlled by a bulk recombination mechanism. We have also shown that these devices may be used as fast, sensitive detectors for a variety of radiation sources.

ACKNOWLEDGMENTS

The authors would like to thank Lonnie Hocker, Paul Zagarino, Chen-wi Lin, and their associates at EG&G Santa Barbara Operations for their invaluable assistance in our detector characterization measurements.

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FIGURE 1
TRANSIENT RESPONSE OF InP:Fe PHOTOCONDUCTOR
(all horizontal scales 200 ps/div)
(detector bias voltage = 500V)