A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

copy 15874/- - 10

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--83-1897

DE83 015237

TITLE InP:Fe PICOSECOND PHOTOCONDUCTORS

AUTHOR(S) R.B. Hammond
R.S. Wagner
H.G. Paulter

NOTICE
PORTIONS OF THIS REPORT ARE ILLEGIBLE.
It has been reproduced from the best available copy to permit the broadest possible availability.

SUBMITTED TO Society of Photo-Optical Instrumentation Engineers

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution or to allow others to do so for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 RM
BY NO 2029 5/81

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EDH

InP:Fe Picosecond Photoconductors

R.B. Hammond, R.S. Wagner, and N.G. Paulter

Electronics Division, Los Alamos National Laboratory
P.O. Box 1663, Los Alamos, New Mexico 87545Abstract

We have measured the impulse response of InP:Fe photoconductors to mode-locked dye-laser excitation. Bias, excitation, and Fe concentration dependence of the impulse response are reported. Linearity of response over two decades in both bias and excitation and independence of transient-response pulse width to both bias and excitation are demonstrated. Correlation is observed between Fe concentration and transient response pulse width. Finally, optical electronic autocorrelation of impulse response consistent with the sampling oscilloscope measurements is reported.

Introduction

In recent years, bulk semiconductor photoconductors have found increasing interest for applications as picosecond optoelectronic pulsers, sampling gates, and detectors.^{1,2} Because of its high carrier mobility (up to $4000 \text{ cm}^2/\text{V-s}$), high resistivity ($>10^7 \Omega\text{-cm}$), and relatively short carrier lifetime ($<1 \text{ ns}$) Fe-doped, semi-insulating InP is an attractive material for these applications. Leonberger and Moulton³ reported the first observation of fast photoresponse in this material. We reported a response of $\sim 100 \text{ ps}$, which was controlled by a bulk mechanism;⁴ later we achieved photoconductive gain greater than unity.⁵ Downey et al.⁶ recently measured photoresponse in InP:Fe devices by autocorrelation. In this paper, we report the bias, excitation, and Fe concentration dependence of impulse response in photoconductors fabricated from InP:Fe. We also report optical electronic autocorrelation measurements of impulse response in this material.

Comparison of photoconductors with photodiodes

An important difference between photoconductors and photodiodes is the mechanisms that determine their response speed. In photodiodes, response speed is determined by the transit time of free carriers between the device electrodes. Response is dependent on the electric field between the electrodes and, thus, on the applied bias. Also, only one (or at most two) charges can be delivered to an external circuit by the photodiode for each photon incident on the device active area (unless avalanche multiplication of carriers is used, which introduces noise and limits speed). In photoconductors, response speed is controlled by bulk recombination of free carriers in the semiconductor. Thus, speed is independent of both the spacing between the electrodes and the bias. There are two resultant advantages of using photoconductors rather than photodiodes. First, photoconductive gain (delivering more than one charge to an external circuit per incident photon) is possible. Second, the photoconductor can be used as an optically activated electronic sampling gate. The principal advantage of photodiodes compared to photoconductors is that speed is achieved by simply placing the electrodes close together without changing any material property. A challenge to obtaining useful high-speed photoconductors is controlling carrier recombination and, thus, response speed in the host material without limiting carrier mobility. In this work, we show that InP:Fe has an excellent combination of short carrier lifetime and high carrier mobility.

Experimental

We have studied bulk-grown, Fe-doped semi-insulating InP with a bulk resistivity of $2 \times 10^7 \Omega\text{-cm}$. We used material cut from several different wafers. For each wafer, the Fe concentration was determined by secondary ion mass spectroscopy (SIMS) analysis. Crystals $5 \times 1 \times 0.5 \text{ mm}$ were cut from the wafers. Thermally evaporated and sintered (425°C) AuGe contacts (80% Au, 20% Ge) were formed on the crystals with contact spacings of 0.5 mm . The finished devices were mounted in 50 μ microstrip transmission lines formed on 1-mm alumina substrates. The InP:Fe devices (Fig. 1) replaced the center conductor in the transmission lines. Microstrip to coaxial transitions were made with SMA bulkhead connectors at 2.5 cm from either side of the InP:Fe device.

Impulse response measurements were performed on these devices with a synchronously pumped, mode-locked dye laser that produced 15-ps pulses of either 600- or 700-nm wavelength at a 4-MHz repetition rate. Impulse response of the InP:Fe photoconductors was measured with both sources using a 30-ps risetime sampling oscilloscope. In most cases, 50 traces were averaged.

Impulse response results

We measured the impulse response of InP:Fe photoconductors using crystals with various Fe concentrations under various bias and excitation conditions. Figure 2 is a typical impulse response transient from an InP:Fe photoconductor recorded with a sampling oscilloscope. The voltage risetime is limited only by the excitation source and the bandwidth of the measurement. The pulse full-width at half maximum (FWHM) is a measure of the photoconductor response speed. For the data reported, the voltage risetimes ranged from 50 to 60 ps.

For detector applications, devices should have current response proportional to light intensity and response speed independent of light intensity. Figure 3 summarizes impulse response data showing these dependences for InP:Fe photoconductors. The devices do indeed show the linear response and excitation-independent speed required for fast photodetector applications.

For sampling gate applications, devices should have current response proportional to bias and response speed independent of bias. Figure 4 summarizes impulse response data showing these dependences. Over the range of these measurements, we find the desired linearity of response and bias-independent speed required for fast sampling gate applications.

The data for Figures 2, 3, and 4, were taken with the same InP:Fe device, which had an Fe concentration of $4 \times 10^{16} \text{ cm}^{-3}$ determined by SIMS analysis. We also measured impulse response on devices fabricated from seven other wafers. These devices showed a systematic variation in response speed with Fe concentration measured using SIMS. The results of these impulse response measurements are summarized in Figure 5. One readily notices a trend of increasing response speed with increasing Fe concentration in the nP crystals. These results suggest that an approach such as that described by Hwang et al.⁷ may be appropriate to describe photoconductive response in InP:Fe.

Autocorrelation measurement of InP:Fe impulse response

A complementary measurement to the conventional sampling oscilloscope measurement of impulse response in photoconductors is optical electronic autocorrelation. In autocorrelation, two identical photoconductors are connected in series, the first acting as a light detector and the second as a sampling gate. This measurement technique was first used by Auston et al.⁸ The configuration of the detection and sampling photoconductors is shown in Figure 6. There are two gaps in the AuGe contact metallization on the InP crystal; the first gap is the detector and the second is the sampler. There are transmission line connections to ground from the contact region between the two gaps. A short light pulse incident on the first gap produces an impulse voltage to the second gap. Another light pulse incident on the second gap causes this impulse voltage to be sampled. The timing between the pulsing by the first gap and the sampling by the second gap can be controlled very precisely if one begins with a single light pulse and splits it with a beam splitter. Then, varying the difference in optical path length of these two optical pulses to the photoconductor gaps can be used to change the relative timing of the pulsing and sampling functions. The average current through the autocorrelation structure:

varies as

$$I_{avg} = \int V(t)V(t + \delta) dt ,$$

where $V(t)$ is the impulse response of a single photoconductor and δ is the relative delay between the pulsing and sampling functions.

Figure 7 shows an autocorrelation measurement of the impulse response of identical InP:Fe photoconductors. The InP crystal used had an Fe concentration of $4 \times 10^{16} \text{ cm}^{-3}$, as determined by SIMS analysis. The autocorrelation is symmetric and has a width consistent with the sampling oscilloscope measurements.

Downey et al.⁶ have reported asymmetric autocorrelation measurements on InP photoconductors in contrast to our result. They attributed this result to poor electrical contacts that caused the devices to respond differently to pulsed and dc biases. In our devices, we see no difference between pulsed and dc biases probably because we used AuGe metallizations sintered at 425°C; (Downey et al used unsintered Au metallizations.) We found previously that these AuGe contacts were necessary to achieve photoconductive gain.⁵

Conclusion

We measured impulse response in InP:Fe photoconductors and found that these devices have desirable characteristics for applications as fast optical detectors and as fast sampling gates. Sensitive response from ~ 65 to ~ 400 ps was observed in crystals with varying Fe concentrations. Optical electronic autocorrelation measurements of response in these devices were consistent with sampling oscilloscope measurements.

References

1. Auston, D. H. and Smith, P. R., "Picosecond Optical Electronics for High-Speed Instrumentation," *Laser Focus*, pp. 89-93 and references therein. April 1982.
2. Mourou, G., Knox, W. and Williamson, S., "Picosecond High-Power Switching and Applications," *Laser Focus*, pp. 97-106 and references therein. April 1982.
3. Leonberger, F. J. and Moulton, P. F., "High-Speed InP Optoelectronic Switch," *Appl. Phys. Lett.*, Vol. 35, pp. 712-714. 1979.
4. Hammond, R. B., Faulter, N. G., Iverson, A. E. and Smith R. C., "Sub-100 ps Bulk-Recombination-Limited InP:Fe Photoconductive Detector," Technical Digest of the International Electron Devices Meeting, pp. 157-160. 1981.
5. Hammond, R. B., Faulter, N. G., Wagner, R. S., Springer, T. S. and MacRoberts, M. D. J., "InP:Fe Photoconductors as Photodetectors," *IEEE Transactions on Electron Devices*, Vol. ED-30, pp. 412-415. 1983.
6. Downey, P. M., Auston, D. H. and Smith, P. R., "Picosecond Correlation Measurements of Indium Phosphide Photoconductors," *Appl. Phys. Lett.*, Vol. 42, pp. 215-217. 1983.
7. Hwang, B.-Y., Lindholm, F. A. and Hammond, R. B., "Methodology for Calculating Turn-Off Transient of Photoconductive Circuit Elements in Picosecond Optoelectronics," *IEEE Journal of Quantum Electronics*, Vol. QE-19, pp. 648-657. 1983.
8. Auston, D. H., Johnson, A. M., Smith, P. R. and Bean, J. C., "Picosecond Optoelectronic Detection, Sampling, and Correlation Measurements in Amorphous Semiconductors," *Appl. Phys. Lett.*, Vol. 37, pp. 371-373. 1980.

Figure 1. Schematic drawing of an InP:Fe photoconductor in a microstrip transmission line. The crystal replaces the center conductor for 5 mm on the 50- Ω transmission line. The microstrip is on a 1-mm-thick alumina substrate, and the center conductor width is also 1 mm (not drawn to scale). Connection from the photoconductor to the microstrip is made with a conductive silver paint (not shown). AuGe contacts are formed on the photoconductor surface to make an active area of 1- x 5-mm.

Figure 2. Averaged impulse response transient from an InP:Fe photoconductor. Excitation was with 15-ps, 600-nm pulses of ~ 50 -pJ energy, producing an approximate electron-hole pair density in the InP of 2×10^{15} cm $^{-3}$. Bias was 300 V. Data were recorded with a 30-ps risetime sampling oscilloscope.

Figure 3. (a) Peak voltage signal of impulse response transients from InP:Fe photoconductor plotted vs relative laser pulse energy. Photoconductor bias was 300 V. Laser pulse energies varied from ~ 10 pJ to ~ 1 nJ, wavelength was 600 nm.

Figure 3. (b) Full-width at half-maximum (FWHM) taken from the same impulse response transients as data in (a).

Figure 4. (a) Peak voltage signal of impulse response transients from InP:Fe photoconductor plotted vs bias voltage. Laser pulse energy was ~ 1 nJ and wave-length was 600 nm.

Figure 4. (b) FWHM taken from the same impulse response transients as data in (a).

Figure 5. FWHM of impulse response transients from various InP:Fe photoconductors plotted vs Fe concentration in the InP crystals. Excitation was 15 ps, ~ 1 -nJ laser pulses, at both 600 and 780 nm. Bias voltage was 300 V.

Figure 6. InP:Fe photoconductor in autocorrelation structure. The InP crystal is 5 mm long and replaces the center conductor in a 50 Ω microstrip transmission line. The crystal has AuGe contacts with two gaps, each 25 μ m wide. The area between the gaps replaces the center conductor of another 50 Ω microstrip line perpendicular to the primary line. Contacts between the photoconductors and the microstrip lines were made with a conductive silver paint (not shown).

Figure 7. Autocorrelation measurement of impulse response from the structure shown in Figure 6. The 1/e half-width is 101 ps, which corresponds to a FWHM impulse response of ~ 70 ps (assuming exponential decay). The laser pulse energy was ~ 20 pJ; wavelength was 600 nm; pulse duration was 0.2 ps; and bias was 30 V.