

AFOSR Final Technical Report (F49620-93-1-0161)

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Abstract

Under the support from AFOSR, we have studied ultrafast optoelectronics in two projects: [1] time-resolved optoelectronic measurements of nitrogen-implanted GaAs crystals and InGaAs; and [2] photoresponse of Si/Ge superlattice and its alloy materials.

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- 1 Y. Jin, D.F. Liu, G.A. Wagoner, W.D. Phillips, T. Sangsari, J. Perkin, M. Alexander, X.-C. Zhang, "Temperature Dependence of THz Emission from <111> GaAs via Trans-Resonant Excitation," Submitted to Appl. Phys. Lett. (1994)
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- 6 S. Hong, Y. Jin, G. Wagoner, X.-C. Zhang, L. Kingsley, "Time-Resolved Optoelectronic Measurements of Nitrogen-implanted GaAs Crystals," Ultrafast Phenomena, **7** (1994)
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[1] Time-Resolved Measurements of Nitrogen-Implanted GaAs Crystals

We compared the measurement of optically induced THz radiation and time-resolved photoreflectance ($\Delta R/R$) from nitrogen-ion implanted GaAs samples, where surface implantation densities ranged from $1 \times 10^8 \text{ cm}^{-2}$ to $5 \times 10^{15} \text{ cm}^{-2}$.

Understanding the effects of electrochemical passivation on the electronic properties of semiconductor surface states is crucial to semiconductor device fabrication. Previous results indicated that the static electric field across the surface of a semiconductor is substantially modified by hydrogen plasma passivation. As an example, after 30 minutes of passivation, the surface field from n(p)-type GaAs samples has been shown to increase by up to a factor of 2(10). Herein, we report the results of our recent measurements of the transient optoelectronic properties of nitrogen-ion implanted GaAs, where the nitrogen ions served as isoelectronic centers and surface implantation densities ranged from $1 \times 10^8 \text{ cm}^{-2}$ to $5 \times 10^{15} \text{ cm}^{-2}$. Optically induced THz electromagnetic radiation and time-resolved photoreflectance ($\Delta R/R$) measurements were made and the results of these two different optoelectronic techniques was compared. Both measurements show strong dependence on implantation density and either technique is a good diagnostic of surface implantation density.

GaAs substrates were cleaved from a single semi-insulating GaAs wafer. The measured resistivity and steady state mobility were over $10^7 \Omega \cdot \text{cm}$ and $4,000 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$, respectively. The substrates were then implanted with nitrogen ions. One GaAs substrate remained unimplanted and served as a reference sample. The implantation was performed on a Varian 350R Medium-Energy & Medium-Current ion implanter. The beam current ranged from $0.18 \mu\text{A}$ to $100 \mu\text{A}$, increasing proportionally with dose level. The typical sample temperature was kept below $80 \text{ }^\circ\text{C}$ and no annealing was performed after ion-implantation. The energy of the incident nitrogen ions was set at 180 keV . Nitrogen ion surface densities ranged from $1 \times 10^8 \text{ cm}^{-2}$ to $5 \times 10^{15} \text{ cm}^{-2}$, with incremental steps alternating between a factor of 2 and 5 successively. The mean value of the damage depth in the samples was approximately $0.6 \mu\text{m}$ which is comparable to the optical absorption length ($\alpha^{-1} = 0.7 \mu\text{m}$ at $\lambda = 810 \text{ nm}$).

The optical source was a mode-locked Ti:sapphire laser, operating at a central wavelength of 810 nm. During the measurement of optically-induced THz radiation emitted from the wafers, the waist of the normally-incident, unfocused optical beam was approximately 4 mm. Further, the wafers were subjected to an external magnetic field of roughly 0.3 Tesla, which was perpendicular to the direction of optical propagation and was applied via pair of permanent magnets. The forward THz radiation was detected by an ultrafast photoconducting antenna. In the time-resolved photorefectance experiment (pump / probe), the laser beam was focused to spot size of approximately 100 μm . Both experiments were performed at room temperature.

Because the unimplanted GaAs wafer was slightly n-type, the direction of its surface depletion field was outward. However, since nitrogen ions are an isoelectronic element for GaAs, after implantation, the field direction reversed. The THz radiation waveforms emitted from a GaAs wafer prior to, and after implantation at $5 \times 10^{11} \text{ cm}^{-2}$ are shown in Fig. 1. The observed polarity flip is associated with a reversal in the direction of the surface depletion field. Fig. 2 displays THz radiation waveforms from several ion-implanted samples with implantation surface densities ranging from $5 \times 10^{11} \text{ cm}^{-2}$ to $5 \times 10^{14} \text{ cm}^{-2}$.

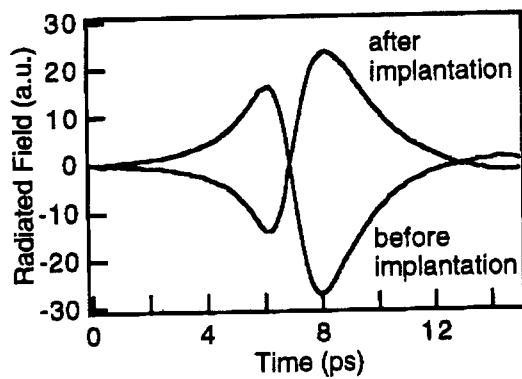


Fig. 1

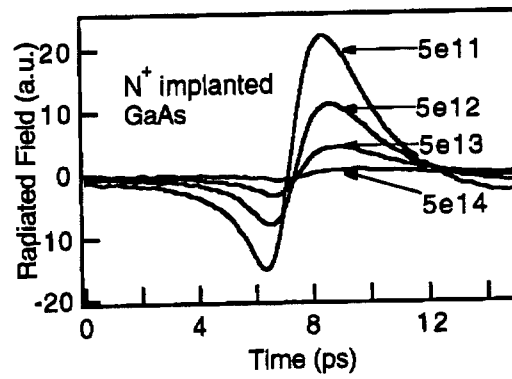


Fig. 2

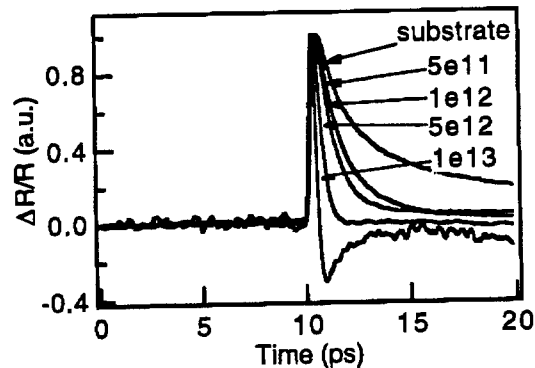
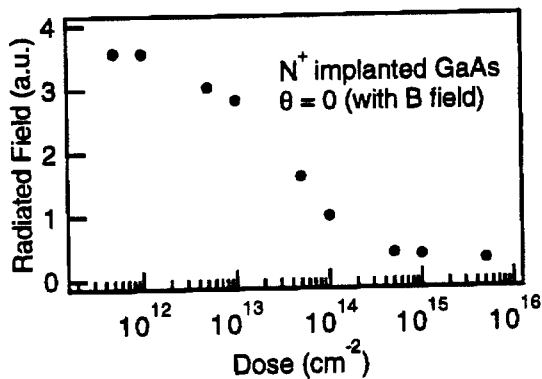


Fig. 3

Fig. 4

Fig. 3 plots the amplitude of THz radiation versus ion dose level. THz signal decreases as surface implantation density increases. Fig. 4 shows normalized temporal waveforms of modulated photoreflectance signals, $(\Delta R/R)$ from both implanted and unimplanted samples. Corresponding with increased implantation density, is a significant decrease in the $\Delta R/R$ waveform decay time. For samples with ion dose levels greater than $1 \times 10^{13} \text{ cm}^{-2}$, decay times as short as 0.35 ps have been observed. Fig. 5 plots the peak values of the photoreflectance signal versus implant density. From samples with implant densities greater than 10^{14} cm^{-2} , we observe a sign change in the peak value of the photoreflectance signal.

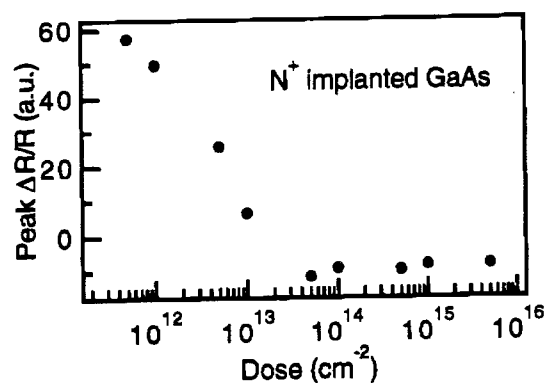


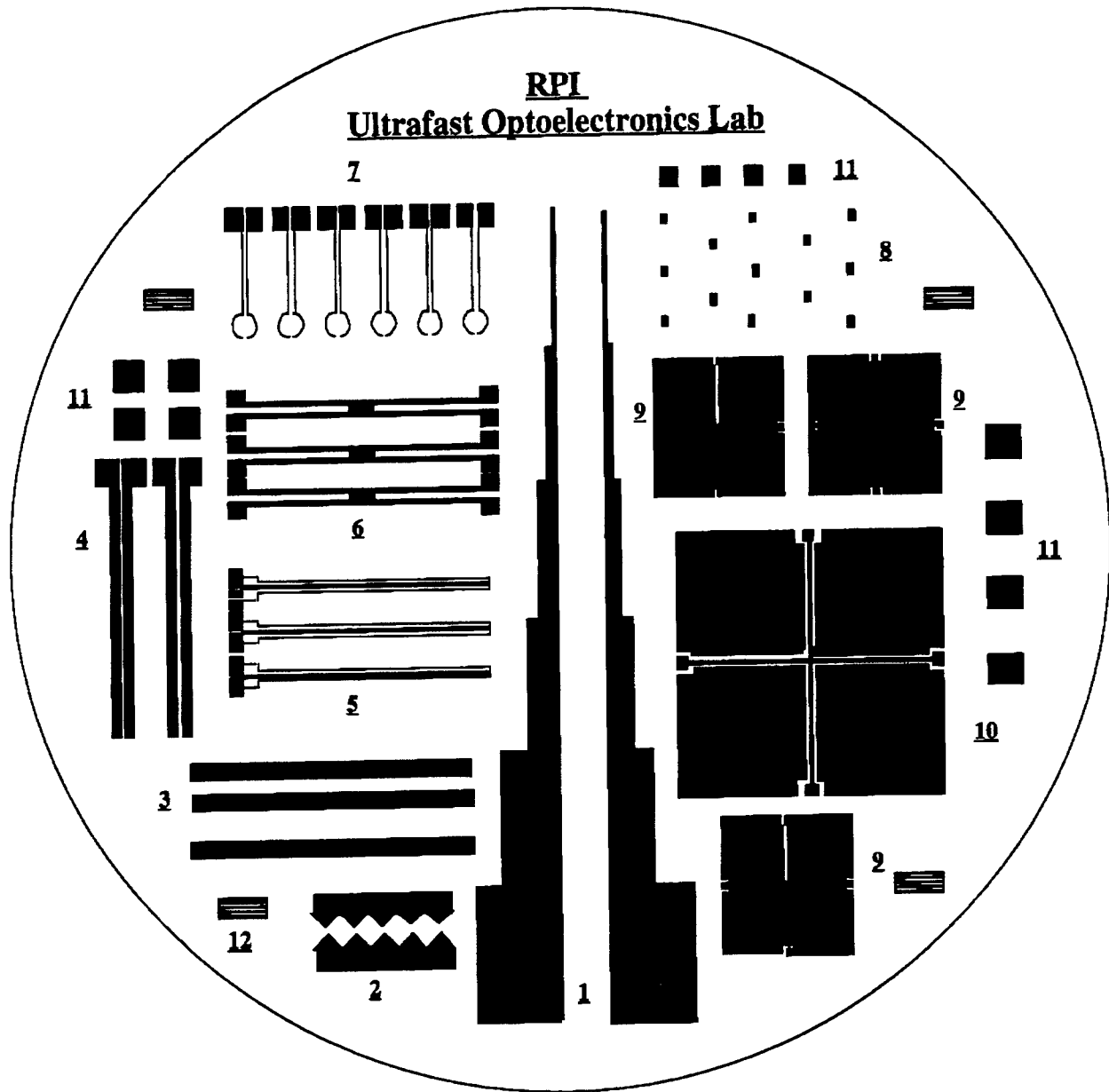
Fig. 5

In summary, we report the measurement and comparison of optically induced THz radiation and time-resolved photoreflectance from nitrogen-ion implanted GaAs samples.

Currently, we are studying the possibility to switch large photocurrent (up to kA) in the THz photoconducting antennas, which is impractical with conventional contacting methods. We believe that the remote magnetic control to the intense THz radiation has the potential to be used in THz beam steering system. We also established the sample exchange program with Raytheon. Now we can get InGaAs samples (both bulk and MBE growth samples) from them. We have measured over 9 different low temperature InGaAs samples sets (alloyed and superlattice samples). Our measurement shows 7.1 to 24 ps carrier lifetime of their low temperature InGaAs. These materials are grown for 1.3 μm detectors.

Si/Ge Auston Switches:

We have designed and fabricated a mask for ultrafast optoelectronic measurement, including carrier lifetime measurement of SiGe materials. The pattern of the mask is shown in Figure 6. This mask has been used to make many antenna structures for several scientists in Air Force Base (Dr. Sam Howelis, Kirtland AFB, and Dr. M. Alexander) and Army Research Office (Dr. B. Guenther).



Structure Description

1. Step electrodes (1)
 - Step height 1 cm
 - Step number 6
 - Electrode width 5, 10, 50, 500, 2000, 5000 μm
 - Gap width 4 mm
2. Zig-zag array (1)
 - Length 1 cm
 - Electrode width 0.5 mm
 - Zig height 1 mm
 - Small gap 0.1 mm
3. Large electrode set (2)
 - Length 2 cm
 - Electrode width 2 mm
 - Gaps 2, 4 mm
4. Small electrode set (2)
 - Pads 1 mm by 1.5 mm
 - Wire width 1 mm
 - Gaps 50, 100 μm
5. Double antenna (3)
 - Electrode pads 1 mm by 1 mm
 - Wire 10 μm
 - Separation 5 μm
 - Top widths 50, 100, 200 μm
6. Dipole antenna (3)
 - Electrode pads 1 mm by 1 mm
 - Length 2 cm
 - Small gap 5 μm
 - Separation 50, 100, 200 μm
7. Magnetic field sensors (6)
 - Electrode pads 1 mm by 1 mm
 - Overall length 1 cm
 - Wire width 10 μm
 - Separation 10 μm
 - Loop radius 50, 100 μm
 - Opening none, 5 μm , 10 μm
8. Square dot detectors (2 x 5)
 - Side length 100 μm and 200 μm
 - Gaps 2, 3, 4, 5 10 μm
 - Distance 5 mm

9. Small Auston switch (3)
- | | |
|------|------------------|
| Size | 1 cm by 1 cm |
| Wire | 10 μm |
| Gap | 10 μm |
| Wire | 10 μm |
| Gap | 5 μm |
| Wire | 5 μm |
| Gap | 2 μm |
10. Large Auston switch (1)
- | | |
|------|------------------|
| Size | 2 cm by 2 cm |
| Wire | 10 μm |
| Gap | 5 μm |
11. Electrode pads
2 mm by 2 mm, 1 mm by 1 mm
12. Manufacture aids: line pair
- | | |
|-------------|-----------------|
| Width | 2 μm |
| Separations | 2 μm |
| Number | 20 |

We have fabricated two Auston switches on Si/Ge superlattice samples. The materials was provided by IBM T.J. Watson Research Center. We sent the samples out for ion implantation. We have test them using 820 nm laser pulse (Ti:sapphire laser). The test indicated the structures were good. 2 to 5 picosecond photoresponses have been achieved. However, at 1.3 μm (measurement done by Dr. Ray Boncek at Rome Lab.), one sample showed no photoresponse and other has a small photoresponse. A SiGe alloy sample shows a better photoconductivity. Recently IBM donated their Si/Ge MBE to Prof. W.I. Wang (Columbia Univ.), so we can not get samples from them within a short time. Currently we are contacting with AT&T Bell Laboratory for new MBE materials, and IBM for MOCVD growth materials.

For the first time, we achieved photocurrent in our magnetic field sensor which is our item 7. These sensors are current loops. The material for photoconductor is LT GaAs. We are able to measure picosecond magnetic pulses. Our signal to noise is better than 150 with a 300 ms of lock-in amplifier integration time.