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Ultrafast Strain-Induced Electronic Transport in a GaAs *p*-*n* Junction Diode

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In this paper, we report the measurement of the electrical current induced by the passage of picosecond acoustic pulses through a GaAs $p-n$ junction diode. The electric current pulses induced in the device without and with applied electrical bias are attributed to an ultrafast piezojunction effect. In conjunction with microwave electronic instrumentation, such a device may be used as a detector in picosecond acoustics experiments.

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I. INTRODUCTION

The application of strain to semiconductor devices such as $p-n$ junction diodes and transistors gives rise to a change in the devices' electrical characteristics [1, 2]. This behavior, which is known as the piezojunction effect, can be exploited to make sensitive stress sensors [3]. The piezojunction effect is primarily due to the effect of the strain on the band edges of the semiconductor via the deformation potential and piezoelectric interactions. Owing to the exponential dependence of the current in $p-n$ junctions on the energies of the band edges, significant changes in the current-voltage $(I-V)$ characteristics are observed. In addition, strain can affect the carrier mobility and valence band density of states, which also contribute to changes in the $I-V$ characteristics.

Previously, the piezojunction effect has been studied only for static or slowly varying strains, but the band parameters of semiconductors are responsive to strain on an ultra-fast (sub-picosecond) timescale. This has been shown in recent picosecond acoustics experiments, where an ultrafast strain pulse has been used to induce transient currents in an n-type epilayer [4] and to modulate, on a picosecond timescale, the optical properties of a quantum well [5] and the photoconductivity of a $p-i-n$ diode [6]. Therefore, it might be reasonable to consider using $p-n$ diodes, in conjunction with currently available high-speed electronic instrumentation, as detectors in ultrafast acoustics experiments. Other potential applications include the acoustically driven generation of ultrashort current pulses for triggering or clocking of electronic systems. Furthermore, if the $p-n$ diode responds to a picosecond acoustic pulse, the fabrication of fast active acousto-electronic devices based on bipolar junction transistors might be possible.

In practice, the speed of the response of a device to an acoustic pulse will be determined by the effects of junction capacitance, charge storage, and minority carrier lifetimes as well as by the external electronic circuit. However, by using semiconductor materials

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with short minority carrier lifetimes, such as epitaxially grown GaAs, it is possible to manufacture small $p-n$ diodes for use at frequencies in the 10s of GHz range. The aim of this work is to investigate the feasibility of electrical detection of an ultrafast strain pulse by using such a GaAs $p-n$ junction diode.

II. THE EXPERIMENT

The experimental setup is shown in Figure 1. The GaAs, fast-recovery, abrupt$p-n$ junction diode was grown by MBE on a 350-μm-thick semi-insulating GaAs substrate. A 1.0-μm-thick n-GaAs layer, doped with Si to a density of 2×10^{18} cm^{-3}, was grown first. On top of this was grown a 0.5-μm-thick p-GaAs layer that was doped with C to a density of 3 $\times 10^{18}$ cm^{-3}. The structure was processed into 200-μm-diameter and approximately 1-μm-tall vertical device mesas, and electrical contacts were made to the p and n layers using AuZnAu and GeAuNiAu, respectively. On the opposite side of the substrate, a $\sim$100-nm-thick Al film was deposited by thermal evaporation. The sample was mounted on a specially designed holder incorporating 50-Ω strip line conductor, low inductance electronic components, and SMA launcher for connection to the cryostat wiring.

In the experiments, which were carried out in an optical cryostat at temperatures between 5 and 300 K, the Al film was excited by pulses from an amplified Ti:Sapphire laser (pulselength = 40 fs; wavelength = 800 nm; and repetition rate 5 kHz). The laser was focused to a spot with a diameter of approximately 150 μm opposite the device, and the intensity on the Al film was on the order a few mJ/cm^2. Strain pulses, generated by the thermoelastic effect in the film, propagated into the GaAs wafer and after about 72 ns, reached the device. The device was biased with a constant voltage, and changes in current induced by the strain pulses led to transient voltage pulses across the 50-Ω load resistor, which were detected using microwave (18 GHz) electronics and a 50-GS/s averaging oscilloscope.

Figure 2 shows an example of the temporal signal obtained from the device. The initial "ringing" feature starting at $t = 0$ is due to direct optical excitation of the device by stray light from the laser pulse. About 72 ns after this, we observe a signal due to the acoustic pulse reaching the device after traversing the substrate at the speed of sound. After another 144 ns, we observe the signal due to the acoustic pulse, which has been reflected back and forth across the sample, and further reflected pulses are seen at later times. We can discount the possibility that the acoustic signal is due to an incoherent heat pulse, firstly, because it is too short in duration and secondly, because it is only observed when the laser excitation is directly opposite the device.

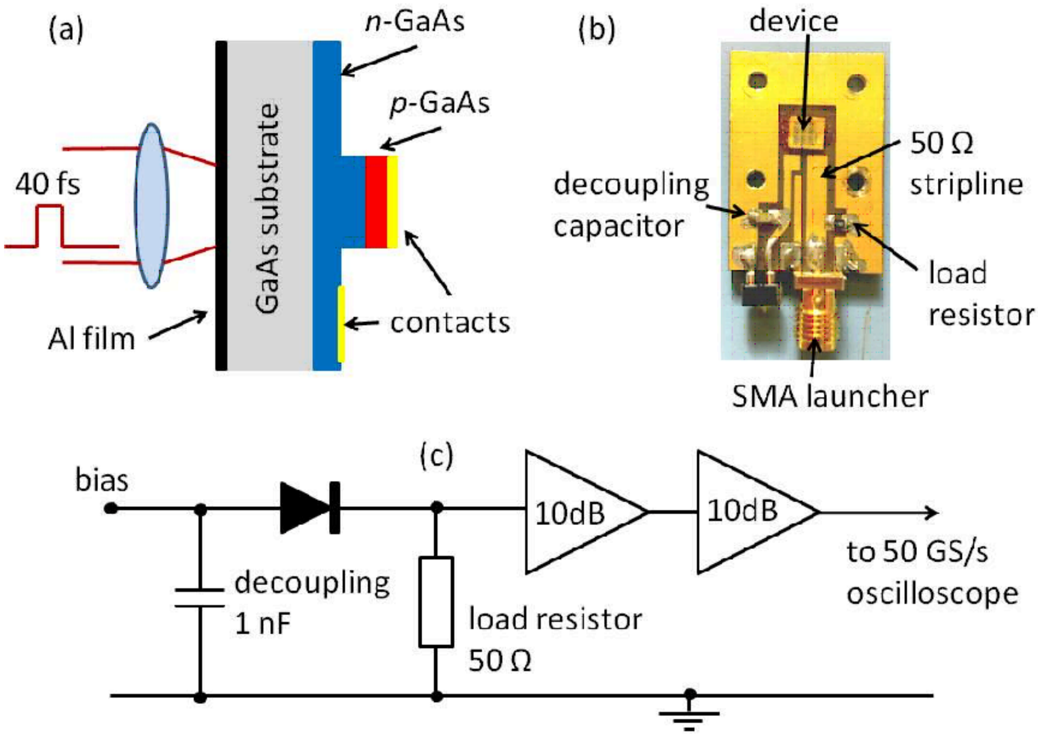

FIG. 1: Experimental arrangement: (a) sample schematic; (b) sample holder; (c) circuit diagram.

III. RESULTS AND DISCUSSION

We now focus our attention on the first pulse, which is detected at about 72 ns. The dependence of this signal on the bias applied to the diode is shown in Figure 3 for an excitation laser intensity of about 5 mJ cm^{-2}. One of the most notable features of this result is that there is a substantial response of the diode to strain at reverse (negative) bias and biases below the diode's forward turn-on voltage. On the other hand, in previous measurements, with static or slowly varying strain, the response was proportional to the forward bias and very small at negative bias. In the absence of strain, the equilibrium electron energy profile of the $p-n$ junction depends on the semiconductor band gap, the Fermi levels in the p and n regions, and the applied bias. At zero and negative bias, a depletion region separates the majority carriers in the p and n regions. A qualitative explanation for our observations is that the passage of the strain pulse modifies the device electron energy profile via the deformation potential. This results in a transitory redistribution of charge within the device to restore equilibrium, giving rise to a current in the external circuit.

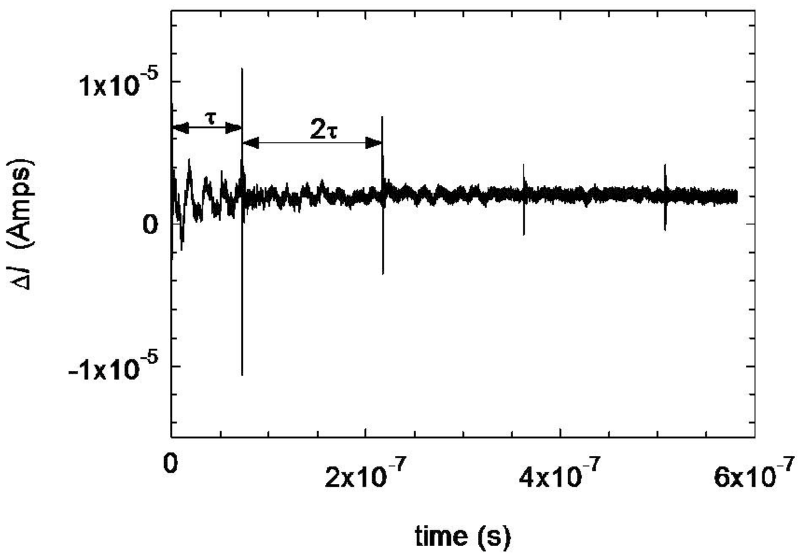

FIG. 2: Signal at an applied forward bias of $1V$. The laser pulse is incident on the Al film at time t = 0. After time $\tau \approx 72ns$, the acoustic pulse reached the diode device. Multiple reflections of the acoustic pulse can be seen, which are separated in time by 2 τ.

To estimate the magnitude of the strain-induced current, we assume an abrupt junction and also assume that the total potential across the junction, V_j, is much greater than kT/e. The latter is valid, even at the lowest temperatures used in the measurements, for reverse bias and for forward bias less than the contact potential ($\sim$1 V). In this case, the diode can be considered as a capacitor with a junction capacitance $C_j(V_j)$. As the strain pulse crosses the junction, it causes a transient change in the $p - n$ contact potential and hence in V_j with the magnitude of $\delta V_j \approx \varepsilon D$, where ε is the magnitude of the strain and D is the deformation potential. This will give rise to a pulse of current in the external circuit of magnitude $\Delta I \approx \varepsilon D C_j/\tau_{RC}$, where τ_{RC} is the time constant of the circuit. The time constant $\tau_{RC} = RC_j$, where R is the load resistance, which gives $\Delta I = \varepsilon D/R$. For a load resistance $R = 50\ \Omega$, and assuming $\varepsilon \sim 10^{-4}$ and $D = 10$ eV, we obtain $\Delta I \sim 2 \times 10^{-5}$, which is on the same order of magnitude as the observed current. The discrepancy between this estimate and the measured value can be attributed to the rise-time of the detection electronics being longer than the duration of the strain pulse by a factor of about four.

As a result of the cancellation of C_j, we would not expect the signal to depend on the magnitude of the bias. In the experiments, only a weak dependence on the bias is seen, with the signal reducing slightly with increasing reverse bias. It should be remembered that the above analysis ignores the changes in the junction capacitance as a result of the strain pulse, effects of leakage resistance, and also the carrier diffusion and recombination times. However, the latter will have a negligible effect on the current if they are shorter than τ_{RC},

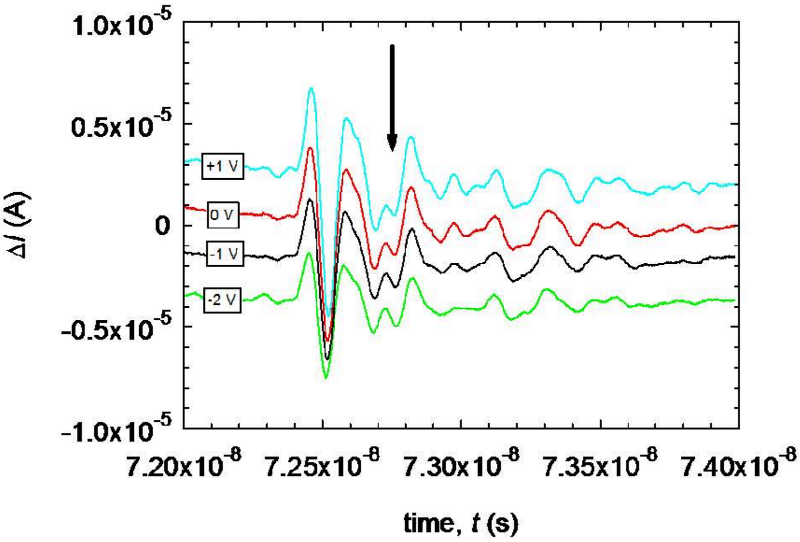

FIG. 3: Signal arriving at $\tau \approx 72ns$ on a zoomed time axis, for four different values of the DC bas applied to the device (traces are offset for clarity). The arrow indicates the expected time of arrival back at the p-n junction of the acoustic pulse reflected from the top of the device.

which is about a nanosecond in our case.

The temporal dependence of the signal is fairly complicated and probably contains elements due to electrical ringing of the external circuit at about 6.5 GHz and recovery from charge storage effects in the diode. However, we can expect there to be a component due to the acoustic pulse that is reflected from the top of the device back to the junction. The return time through the 0.5-μm-thick $p-$GaAs layer and 220-nm-thick Au contact metallization is, in total, about 350 ps, which is indicated by the vertical arrow in the figure and corresponds to what appears in the data as a secondary echo. The rise time of the initial pulse ($\sim$50 ps) is probably limited by the bandwidth of the detection electronics; it is certainly longer than the expected duration of the incident acoustic wave packet.

The amplitude of the generated strain pulse is proportional to the laser intensity used to excite the Al film transducer. Therefore, we would expect the signal amplitude to be proportional to the intensity, as observed in the experiments and shown in Figure 4 for 0 V bias. It is also observed that the start of the rise of the signal moves to earlier times, which is possibly due to acoustic dispersion and nonlinearity effects in the GaAs substrate.

Although all the data shown in Figures 3 and 4 were taken with the sample at a temperature of about 6 K, the diode is also able to detect the acoustic pulse at temperatures up to and above 300 K. Figure 5 shows the signals at 0 V bias for three different temperatures up to 300 K. There is little change in the signal from 6 K up to about 50 K. However,

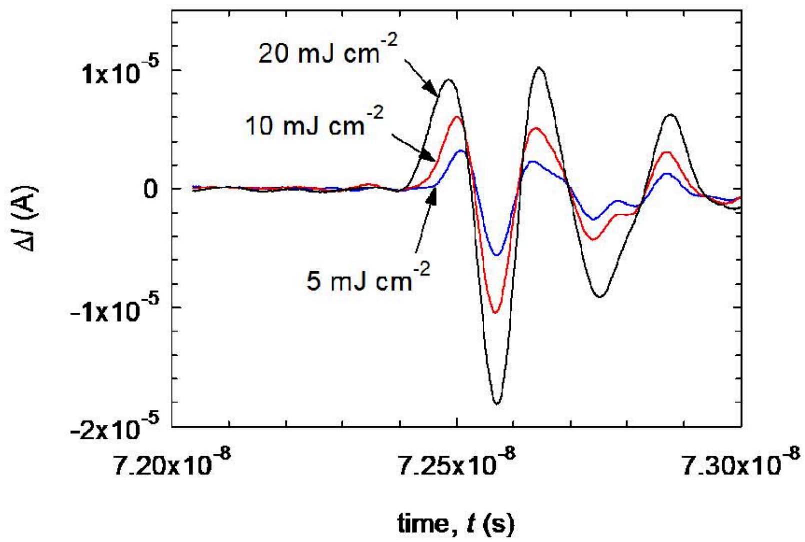

FIG. 4: Signal at 0 V bias for three different values of the excitation laser intensity.

compared to the signal at 50 K, by 300 K, the signal has reduced in amplitude by a factor of about five, and the arrival time is delayed by about 700 ps. According to the simple model of the diode response described above, there should be no strong temperature dependence of the signal due to the sensitivity of the diode. The decrease in the signal amplitude with increasing temperature is most likely due to increased attenuation of the acoustic packet as it traverses the substrate. Increasing the temperature of the substrate also leads to an increase in the time of flight of the acoustic pulse, which accounts for the signal delay.

IV. CONCLUSIONS

In summary, we have shown that a GaAs $p-n$ junction diode in conjunction with high-speed signal acquisition electronics can be a fast and sensitive detector of ultrafast acoustic pulses. We have presented a qualitative explanation of the observations in terms of an ultrafast "piezojunction" effect. However, more work is required to fully account for the temporal and bias dependence of the signal.

We are currently working on incorporating the junction within a heterojunction bipolar transistor to make a "phonotransistor" device (analogous to a phototransistor), which should be much more sensitive due to the transistor's amplifying action. Also, we believe a higher-speed response can be possible by using a majority carrier device such as a Schottky diode and also a smaller device mesa to reduce junction capacitance.

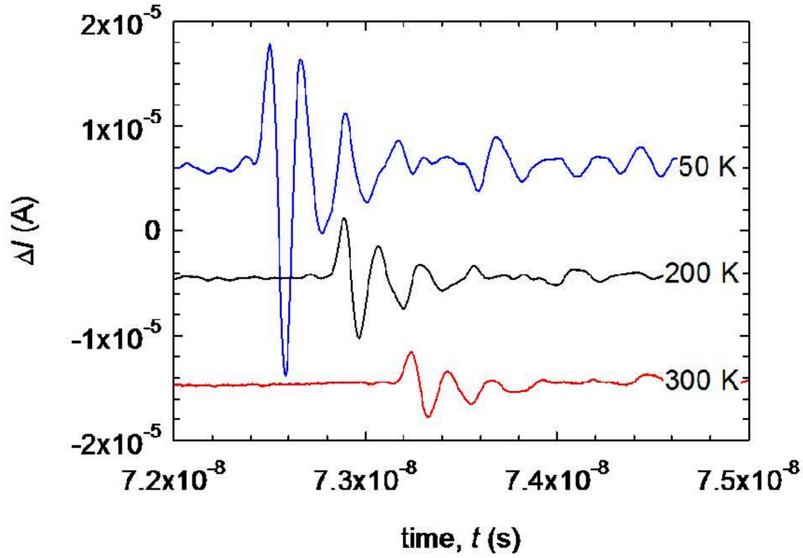

FIG. 5: Signals at 0 V bias for three different sample temperatures (traces are offset vertically for clarity).

Acknowledgments

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