Ultrafast Strain-Induced Current in a GaAs Schottky Diode

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Picosecond acoustic pulses generated by femtosecond laser excitation of a metal film induce a transient current with subnanosecond rise time in a GaAs/Au Schottky diode. The signal consists of components due to the strain pulse crossing the edge of the depletion layer in the GaAs and also the GaAs/Au interface. A theoretical model is presented for the former and is shown to be in very good agreement with the experiment.

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The application of strain to a semiconductor changes the band energies and correspondingly the band gap. This results in changes of the optical and electrical properties of semiconductor devices. In devices such as *p*-*n* junction diodes and bipolar transistors the effect of strain on the electrical characteristics is known as the piezojunction effect [1,2] and has been exploited to make sensitive stress sensors [3].

Previously, the piezojunction effect has been studied only for static or slowly varying strains, but it has been shown recently that by using the methods of picosecond acoustics it is possible to modulate by strain the band parameters of semiconductors on an ultrafast (picosecond) time scale [4–6]. If the piezojunction response is fast enough, it might be reasonable to consider using junction devices, in conjunction with currently available high speed electronic instrumentation, as detectors in ultrafast acoustics experiments as an alternative to optical probing of picosecond strain pulses [7]. Other potential applications include the acoustically driven generation of ultrashort current pulses for triggering or clocking of electronic systems and generation of THz electromagnetic radiation.

The aim of this work is to realize the electrical detection of an ultrafast strain pulse using a junction device. As an object for studies we have chosen the gold Schottky contact on an *n*-GaAs layer. The rationale for using Schottky devices in this application is that, due to the rapid recombination of carriers in the metal, they typically have very fast response times and so are widely used in mm-wave applications.

The experimental arrangement is shown in Fig. 1(a). A 1.0 μm-thick *n*-GaAs layer, doped with Si to a density of $n_D = 6 \times 10^{17}$ cm^{-3}, was grown by molecular beam epitaxy on a semi-insulating GaAs substrate with thickness $d_0 = 380$ μm. On the top of this, a 200 nm-thick Au Schottky contact was deposited. The structure was processed into 200 μm-diameter and approximately 1 μm-tall vertical device mesas and a GeAuNiAu Ohmic contact was made to the *n*-GaAs layer. The sample was mounted on a specially designed holder incorporating 50Ω strip line conductor, low inductance electronic components, and microwave coaxial launcher for connection to the wide-bandwidth cryostat wiring. Figure 1(b) shows the Schottky device's current-voltage (I-V) characteristics at a temperature of 5 K. The device turns on at a forward bias of +0.7 V and reverse breakdown occurs at about −5 V.

In the experiments, which were carried out in an optical cryostat at temperatures T between 5 and 300 K, a ~100 nm-thick Al film deposited on the opposite side of the substrate to the Schottky device 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 of diameter 150 μm opposite the device, and the intensity on the Al film was in the range 1–10 mJ/cm^2. As a result a strain pulse $\eta(x, t)$ was injected into the substrate from the Al film [7]. The pulse corresponds to a compression impact followed by a tension part, and the shape of $\eta(x, t)$ can be modeled well by a derivative of a Gaussian function with total duration of approximately 20 ps. The pulse propagated in the x direction, perpendicular to the surface with the Al film, with the velocity $s_{\mathrm{GaAs}} = 4.8 \times 10^3$ m/s of the longitudinal sound in GaAs [8] and, after time delay $t_0 = d_0/s_{\mathrm{GaAs}} \approx 79$ ns, reached the Schottky device. The device was biased with a

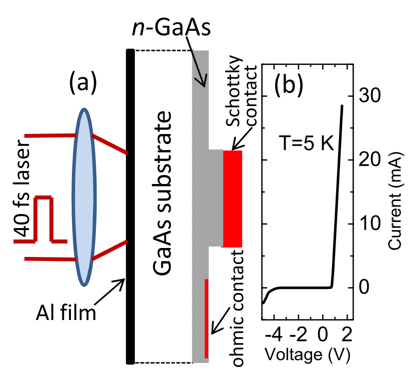

FIG. 1 (color online). (a) The scheme of the sample and experiment with picosecond strain pulses; (b) current-voltage (I-V) characteristics of the Schottky device.

constant voltage V_b, and changes in current $\Delta I(t)$ induced by the strain pulses led to transient voltage pulses across the 50Ω load resistor, which were detected using microwave electronics and a digital sampling oscilloscope. The rise time of the measurement system was limited by the oscilloscope bandwidth to be about 30 ps and, with a sufficiently high signal-to-noise ratio obtained by signal averaging we could measure temporal shifts to a resolution of ~1 ps.

The experimental results are shown in Fig. 2. The inset (left) shows an example of the signal $\Delta I(t)$ obtained from the device at $T = 5$ K. The initial feature at $t = 0$ is due to direct optical excitation of the device by stray light from the laser pulse. After this at $t \approx t_0 = 79$ ns we observe a sharp spike due to the strain pulse reaching the device. Further at $t = 3t_0 = 237$ ns we observe the signal due to the strain pulse which has been reflected back and forth across the sample, and further reflected pulses are seen at intervals of $2t_0$. We can discount the possibility that this signal is due to an incoherent heat pulse, first because it is too short in duration and second because it is observed only when the laser excitation point is located directly opposite the device.

We now focus our attention on the first pulse, detected at about 79 ns with subnanosecond resolution. Figure 2 shows the temporal signals $\Delta I(t)$ measured for six values of the reverse bias, in the range $V_b = 0$ to -5 V. It is clearly seen that temporal evolution of $\Delta I(t)$ depends on V_b. Considering the positive peaks in $\Delta I(t)$ occurring at about 79 and 79.2 ns, and which are marked by the dashed lines in Fig. 2. The earlier of these clearly moves to shorter times with the increase of reverse bias. In parallel, the later peak moves to longer times. Between these two positive peaks, $\Delta I(t)$ changes sign while V_b is varying from zero to -5 V, and, for $V_b < -2$ V, the temporal position of the maximum is almost independent on V_b. In the inset (right) the arrival time of the $\Delta I(t)$ signal as a function of V_b is shown by the squares. To determine the arrival time, we took the time at which the maximum of the derivative of the rising edge of the earlier peak occurred.

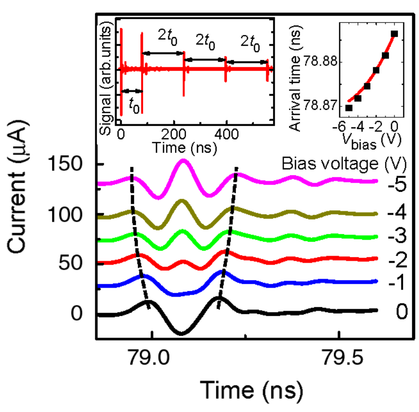

FIG. 2 (color online). The temporal responses of the Schottky device to a strain pulse measured at $T = 5$ K, for six different values of V_b (the traces are vertically offset for clarity). The insets show the signal measured at $V_b = 0$ on an extended time axis (left), and (right) the dependence on V_b of the time of the start of the signal.

The measurements were also performed at temperatures up to 300 K and for forward biases $V_b > 0$. At room temperature the amplitude of $\Delta I(t)$ is a factor of about 5 smaller than at $T = 5$ K. The signals $\Delta I(t)$ at $V_b > 0$ are accompanied by a large stationary current through the Schottky diode and, therefore, Joule heating of the sample. The measured $\Delta I(t)$ in this case has an amplitude similar to that described above, while its temporal evolution is quite different from when $V_b < 0$. We will not consider any further the details of the experiments carried out under these conditions, because we would need to take into account the thermal effects for the strain pulse evolution, which lies out of the scope of the present letter.

The aim of the following discussion is to understand the mechanism for the modulation of $\Delta I(t)$ by the picosecond strain pulses. In the static case, strain modifies carrier transfer through the Schottky barrier via variation of its height or tunneling transmission. In earlier experiments measurements with static or slowly varying strain in semiconductor p-n junctions, the response was proportional to the forward bias and very small at negative bias [2]. One of the most notable features in our experiments is that there is a substantial response of the device to the strain at reverse bias ($V_b < 0$). Thus to explain the results with the strain pulses we have to consider mechanisms which are fundamentally different from the static case, and here the dependence of temporal evolution of $\Delta I(t)$ on V_b presented in Fig. 2 plays a crucial role.

We propose a mechanism that gives a strong electrical response due to the dynamical screening of the potential perturbation caused by the strain pulse. Such screening is accomplished by electron redistribution in the semiconductor and gives rise to a displacement current through the diode. This electrical response becomes possible because of the strongly nonuniform distribution of carriers in the Schottky diode. Figure 3(a) shows the electron band diagram of the (degenerate) Schottky diode under equilibrium conditions (in the absence of a strain pulse). At $V_b < 0$ the electric current is negligible, and the electron density at a distance x into the semiconductor from the metal-semiconductor interface $n(x)$ is close to the equilibrium value $n_0(\mu(x))$ corresponding to the local value of electrochemical potential: $\mu(x) = E_F - \varphi(x)$, where E_F is the Fermi energy and $\varphi(x)$ is the band edge potential energy which can be found from the solution of the Poisson equation with the relevant boundary conditions. The width x_d of the depletion region is well described by the analytical equation

$$x_d \approx \left[\frac{2\varepsilon\varepsilon_0(\varphi_0 - E_F - eV_b)}{n_D e^2}\right]^{1/2}, \qquad (1)$$

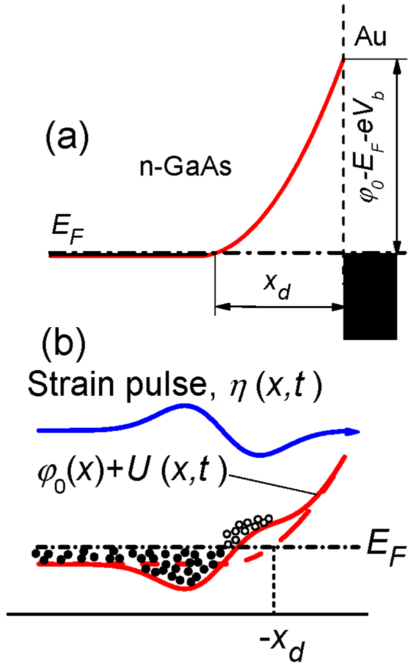

FIG. 3 (color online). (a) Electron band diagram of the Schottky device under equilibrium conditions; (b) the schematic demonstration of the effect of the strain pulse incident on the edge of the depletion layer at distance x_d from the GaAs/Au interface.

where φ_0 is the height of the Schottky barrier at $V_b = 0$, and $\varepsilon = 12.9$ is the static permittivity of the GaAs semiconductor. The I-V measurements [Fig. 1(b)] give the value $\varphi_0 = 0.7$ eV, and Hall measurements of the n-doped GaAs layer give $n_D = 6 \times 10^{17}$ cm^{-3} (3×10^{17} cm^{-3}) at $T = 300$ K (4.2 K) and, respectively, at 4.2 K $E_F \sim 20$ meV above the bottom of the conduction band. Thus from Eq. (1) for our device we get $x_d = 60$ nm (165 nm) for $V_b = 0(-5$ V).

Figure 3(b) demonstrates the case of the band diagram fragment in the presence of a symmetric bipolar strain pulse $\eta(x, t)$ propagating in the GaAs towards the Schottky barrier. At each x and t the strain modifies the energy of the band edges shifting them in accordance with the deformation potential model on a value $U(x, t) = \Xi\eta(x, t)$, where Ξ is the deformation potential for electrons in GaAs. The value of $\Xi(\approx -6$ eV) is taken from studies of the optical band gap under uniaxial strain [9]. This perturbation is partially screened by the free electrons, which undergo a spatial redistribution. Since the characteristic frequency of the strain pulse (~ 50 GHz) is much less than the dielectric relaxation rate ($\sigma/\varepsilon\varepsilon_0$, where σ is the conductivity), screening occurs in a quasistatic way; i.e., the electron density is $n(x, t) = n_0(\mu'(x, t))$, where $\mu'(x, t) = E_F - \varphi(x) - U(x, t) - \delta\varphi(x, t)$, and $\delta\varphi$ is electrostatic energy induced by redistribution of the electrons. The total charge Q induced by the electron redistribution is

$$Q(t) = -eS \int dx\{n_0(\mu'(x, t)) - n_0(\mu(x))\} \qquad (2)$$

where S is the device cross section. If the strain pulse is located within the neutral region of the device, Q is constant and so no current is induced. However, when the strain passes through the region where Q is not constant an electric current in the circuit is generated. It is seen in Fig. 3(b) that the first such region encountered by the strain pulse on its way towards the GaAs/Au interface is the edge of the depletion layer at $x = -x_d$ in the GaAs. Then, the time when the electrical response to the strain pulse starts to appear should depend on x_d, and qualitatively, in accordance with Eq. (1), the electrical response should move to earlier times when applying a more negative V_b, as shown by the solid line in the right inset to Fig. 2. Upon reaching the top of the Au Schottky contact, the strain pulse is reflected and arrives back at the depletion layer edge after a time $\tau = 2(x_d/s_{\mathrm{GaAs}} + d_{\mathrm{Au}}/s_{\mathrm{Au}})$, where $s_{\mathrm{Au}} = 3.36 \times 10^3$ ms^{-1} is the speed of longitudinal sound in gold [10]. This gives rise to the positive peak in $\Delta I(t)$ at $t \approx 79.2$ ns [see Fig. 2] and, in agreement with the proposed mechanism, the peak moves to later times with increasing negative bias because x_d increases.

For the quantitative analysis we have calculated $\delta\varphi(x, t)$ from the Poisson equation and found that the behavior of the induced current, $\Delta I(t)$, depends on the spectral width of the strain pulse, $\Delta\omega$. For our experiment, two important conditions are fulfilled: first, $\Delta\omega RC \gg 1$, where $R \approx 75\ \Omega$ is the resistance of the whole structure, including external resistance and resistance of the conductive regions of the diode, and $C \approx \varepsilon\varepsilon_0 S/x_d \approx 30$ pF is the junction capacitance; and, second, the characteristic spatial scale of the pulse $\Delta\omega/s_{\mathrm{GaAs}}$ is larger than the width of the transitional region at the edge of depletion layer. Under these conditions $\Delta I(t)$ is roughly proportional to the strain $\eta(x, t)$ at $x = -x_d$. This is seen in Fig. 4 where results of numerical calculations of $\Delta I(t)$ for six values of reverse bias in the range $V_b = 0$ to -5 V are shown. Here the initial strain pulse generated in the metal film is assumed to be 20 ps wide and have amplitude of 7.5×10^{-4} as shown in the (top left) inset to Fig. 4. Because of acoustic nonlinearity and dispersion effects in GaAs, upon reaching the Schottky device the initially generated strain pulse evolved into a train of acoustic solitons on the leading edge followed by a dispersive tail of high-frequency modes [11,12] (see right inset in Fig. 4). Reflections of this pulse from the GaAs/Au interface and the sample surface are taken into account in accordance with acoustic mismatch theory [13]. The calculated response contains sharp features consistent with the evolved pulse shape, which implies that the Schottky device is theoretically able to respond to the strain on a picosecond time scale. However, to produce the curves in Fig. 4, we have applied a low-pass Butterworth digital filter [14] with a cutoff at 12.5 GHz to the calculated response in order to account for the finite

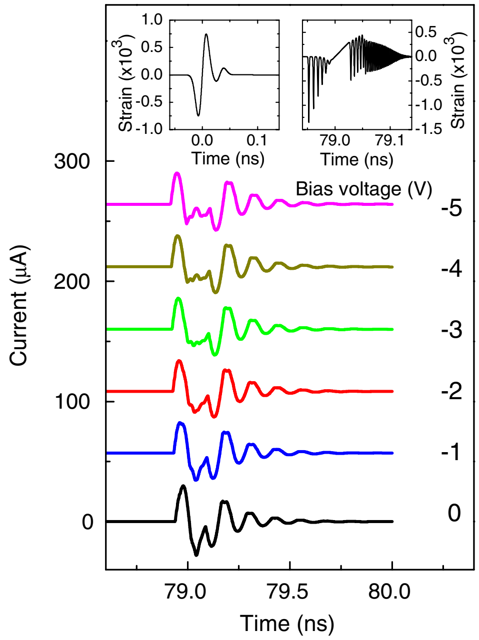

FIG. 4 (color online). Theoretical calculations of the temporal profile of the signal due to the strain pulse crossing the edge of the depletion region for six different values of V_b. The insets show the initially generated strain pulse in the Al film (left), and (right) the strain pulse which reaches the Schottky device.

bandwidth of the measurement system. The first peak in the calculated curves corresponds to the arrival of the incident strain pulse to the edge of the depletion region in GaAs. The next major peak appears with a delay of 200–250 ps (depending on the bias), and corresponds to the echo pulse reflected from the top surface of the Au contact. Further, smaller, peaks at later times are the echoes due to the multiple reflections in the Au film and the corresponding transmission of each echo back into the GaAs at the Au/GaAs interface. The amplitude of the first peak in the calculated response is in fair agreement with that of the measured response, being only a factor of about 2 larger. A possible reason for this difference is that, in the experiment, the width of the acoustic pulse is about 3/4 the width of the device mesa, whereas the present model assumes the pulse is uniform across the entire mesa.

An electrical response is also expected to appear when the strain pulse crosses the semiconductor-metal interface. This contribution to the $\Delta I(t)$ signal will appear later than that from the edge of GaAs depletion layer, and it will not temporally shift with V_b, because the spatial position of the interface does not change with V_b. The peak for which the temporal position, $t \approx 79.08$ ns, is almost independent on V_b, for $V_b < -2$ V, in the measured $\Delta I(t)$ (Fig. 2), could be the feature related to the strain pulse detected at the GaAs/Au interface. This peak clearly becomes stronger at larger absolute values of V_b. However, the lack of available information about strain-induced transport effects in metal does not allow us to make a quantitative analysis in this case and so the peak is not present in the theory curves in Fig. 4.

In summary, we detect a strong subnanosecond electrical response to the picosecond strain pulse in a Schottky diode. A model is proposed where an electrical signal is generated when the strain pulse crosses the edge of the depletion layer in a degenerate semiconductor layer. Very good agreement of the theoretical and experimental dependencies of the signal arrival time on V_b, and the close absolute values of the measured and calculated amplitudes of $\Delta I(t)$ support the validity of the proposed model. A signal component corresponding to the strain pulse incident at the abrupt semiconductor-metal interface is also seen. The results show the feasibility of ultrafast control of the transport properties of devices using sound. Furthermore, now that air-dielectric Schottky diodes for millimeter wave applications are available as well as sampling oscilloscopes working to ~100 GHz, the time-resolved detection of sub-THz acoustic signals by an all electrical technique becomes possible.

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