Improved Performance of GaAs-Based Terahertz Emitters via Surface Passivation and Silicon Nitride Encapsulation

Carl Headley, Lan Fu, Senior Member, IEEE, Patrick Parkinson, Xinlong Xu, James Lloyd-Hughes, Chennupati Jagadish, Fellow, IEEE, and Michael B. Johnston

Abstract—We have improved the stability and performance of terahertz (THz) photoconductive (Auston) switches using a combination of (NH₄)₂S surface passivation (SP) and silicon nitride (Si₃N₄) encapsulation. The influences of SP and encapsulation on the ultrafast electron dynamics in GaAs were examined using THz emission spectroscopy and optical pump–THz probe spectroscopy. The power of THz radiation from the surface of photoexcited GaAs increased by a factor of 5 after passivation and encapsulation, while the process lengthened the trapping time for photoexcited charge carriers. By fabricating and assessing the performance of photoconductive switches, we found that passivation and encapsulation increased the average THz power generated fourfold.

Index Terms—Photoconductive switch (PCS), surface passivation (SP), terahertz (THz), time-domain spectroscopy.

I. INTRODUCTION

ONE METHOD of generating terahertz (THz) radiation for the technique of THz time-domain spectroscopy (THz-TDS) utilizes photoconductive switches (PCSs) that are illuminated by a pulsed femtosecond laser. In order to maximize the output from a PCS, one may increase the applied electric-bias field and the intensity of the laser beam incident on the PCS. However, in doing so, this may limit the operational lifetime of the PCS [1]. Hence, other methods are sought to maximize the THz radiation output and efficiency of PCSs.

A drawback of using GaAs is that bonds are exposed and left “dangling” after the surface of GaAs has been cleaved [2]. These bonds act as trapping centers for photoexcited charge carriers and therefore reduce the conductivity of the material. One method to counteract this trapping effect involves using sulfur in a surface-passivation (SP) process to bridge the broken covalent bonds on the surface of GaAs [3]. It was demonstrated in [4] that this SP treatment results in an increased THz output power. However, it was found that surface-passivated (SP) GaAs PCS emitters tend to show a degraded performance over time, which was attributed to the oxidation of the treated surfaces under continued exposure to air [4].

One method of preventing surface oxidation is to block the interaction of the sulfur atoms and oxygen by encapsulating the semiconductor with a layer of silicon nitride (Si₃N₄). The effects of SP and encapsulation (or overpassivation) using Si₃N₄ on GaAs have been well studied. Previous studies utilized techniques such as reflection high-energy electron diffraction (RHEED) [5], [6], X-ray photoelectron spectroscopy (XPS) [7], [8], photoluminescence [9]–[11], and capacitance–voltage measurements [12], [13]. Relatively few studies have focused upon the application of SP and encapsulation for the improvement of THz devices.

The work described in this paper was undertaken to ascertain whether a PCS with Si₃N₄ on SP GaAs would result in a higher output power of THz radiation and an enhanced resistance to oxygen. The first part of this paper reports THz emission measurements that investigated the properties of the in-built surface electric field. The second section concerns optical pump–THz probe (OPTP) spectroscopy to look for any changes in photoconductivity. Finally, the third part covers THz PCS emission to ascertain whether THz radiation generated from electrically driven sources is also enhanced using the new encapsulation method.

II. METHODS

The samples were all prepared from wafers of semiinsulating (SI) GaAs of approximately 11 mm × 11 mm square and 0.38 mm thickness. The sample surfaces were first etched with H₂SO₄:H₂O₂:H₂O=5:1:1 for 1 min, then passivated in 20% (NH₄)₂S for 10 min. The Si₃N₄ encapsulation layer (100 nm) was deposited by plasma-enhanced chemical vapor deposition (PECVD) at 100 °C for samples used in THz PCS emission measurements and at 70 °C for samples used in the THz emission and OPTP measurements. The PCS emitters were defined using photolithography and subsequent Ge:Au metallization. Alloyed Ohmic contacts were made by annealing at 380 °C for 1 min.

For the SiN encapsulated PCSs a buffered HF etch was used before metalization to remove the Si₃N₄ in the region of the contacts, followed by an etch in 10% HCl to remove the native oxide.

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of the GaAs, red that of GaAs. The increased $N_P/N_E = 90$ layer, and less than 3% with the film. SP GaAs, SP GaAs, and antireflection coating from free space the layer is negligible at 800 nm). The SP GaAs data were shown in Fig. 1(c). It is important to note that the polarity of the THz transient from the passivated samples is opposite to the polarity of the transient emitted from the reference GaAs wafer [see Fig. 1(c)]. This flipping effect is clear evidence that our passivation technique successfully suppresses the states at the surface of GaAs that create the surface electric field, and suggests that passivated GaAs acts more like a photo-Dember emitter than a surface-field THz emitter [4]. In the SP GaAs sample, surface recombination was less substantially suppressed (as the lifetime reported in Section IV), and both mechanisms are likely to contribute. The relative contributions of surface-field THz emission and photo-Dember emission can be studied computationally via Monte Carlo simulations with different surface pinning energies [4]. Furthermore, the similarity between the transients shown in Fig. 1(a) and (b) confirm that the encapsulation process does not degrade the passivation. The encapsulation does, however, preserve the passivation effect over time.

The spectra calculated from the transients are shown in Fig. 1(d). The spectra of the two passivated samples are similar, while the unpassivated sample exhibits a reduced power at low frequency, presumably as a consequence of the differing emission mechanism. The emitted power from each sample was calculated by integrating the spectra shown in Fig. 1(d) between 0.2 and 4 THz. The $\text{Si}_3\text{N}_4$ SP GaAs sample emitted $4.2 \times$ the power emitted by the GaAs reference sample, whereas the SP GaAs sample yielded a value $1.7 \times$ that of GaAs. The increased power emitted from the encapsulated sample can be explained in terms of the transmission of laser radiation into the sample owing to the lower reflectivity with the SiN layer.

IV. TIME-RESOLVED PHOTOCONDUCTIVITY

The performance of a THz PCS is to a large part determined by the photoconductivity of the device within a few picoseconds after photoexcitation. Thus, by measuring the conductivity of a material as a function of time, we can not only reveal information about the ultrafast charge carrier dynamics in that material, but we can also assess its suitability as a substrate for fabricating PCSs on. We used OPTP spectroscopy to measure the time-resolved photoconductivity of our samples, which has been used previously to study surface recombination in pristine [17] and passivated [4] bulk semiconductors. In the particular measurements described here, the THz and optical pump (1/e) beam waists were 2.28 and 2.80 mm, respectively, the pump fluence was calculated to be 35 nJ/(cm$^2$-pulse), and the detector was a (1 1 0) ZnTe crystal of 1 mm thickness.

The THz emission measurements from semiconductor surfaces are sensitive to the space-charge-induced electric field near the surface [14], and hence are an excellent probe of surface chemistry. When a GaAs surface is illuminated with pulses from a femtosecond laser oscillator, the two main mechanisms that contribute to emission of THz radiation are: 1) the acceleration of charge in the surface electric field of the sample and 2) the photo-Dember effect [15]. An effective passivation of the GaAs surface reduces the surface electric field in the depletion region, and therefore, severely reduces the contribution of the first mechanism [4].

In this study, the THz emission from the surface of the samples was collected using a 45° reflection geometry [see Fig. 1(a)], with a setup similar to that described in [16], and with an incident beam power of 180 mW. The THz electric field was detected using electro-optic sampling with a (1 1 0) ZnTe detection crystal of 2-mm thickness.

The laser used in all experiments was an IR Ti:sapphire laser (Mai Tai, Spectra-Physics) that had an output power of 0.84 W and center wavelength of 800 nm, pulse duration of 100 fs, and a repetition frequency of 80 MHz. The measurements were all taken under vacuum (~0.1 mbar).

III. THz SURFACE EMISSION

THz emission measurements from semiconductor surfaces are sensitive to the space-charge-induced electric field near the surface [14], and hence are an excellent probe of surface chemistry. When a GaAs surface is illuminated with pulses from a femtosecond laser oscillator, the two main mechanisms that contribute to emission of THz radiation are: 1) the acceleration of charge in the surface electric field of the sample and 2) the photo-Dember effect [15]. An effective passivation of the GaAs surface reduces the surface electric field in the depletion region, and therefore, severely reduces the contribution of the first mechanism [4].
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Fig. 2. Measured conductivity of the photoexcited carrier population as a function of time after excitation. The black solid lines show the fittings to the datasets. The inset shows the experimental geometry on a GaAs wafer, the wavy (green) arrow represents the incident optical pump beam at 800 nm and the straight (orange) arrow represents the incident and exiting THz probe beam. The SP GaAs data were taken 311 days after the passivation process.

The curves in Fig. 2 show the photoconductivity of each sample (measured at room temperature) as a function of time $\sigma(t')$ after photoexcitation. The photoconductivity data exhibit a double exponential decay: we attribute the shorter time constant to the initial trapping of photogenerated electrons at the surface, and the longer time constant to the recombination of electrons in the bulk GaAs. As our samples were cleaved from the same wafer, the trapping time attributed to bulk GaAs should be identical for all our samples. Therefore, when fitting the data, we applied the constraint that the longer time constant should be common across all samples. Using this constrained global fitting procedure, we found that the time constant for photo injected electrons in GaAs was $5.5 \pm 0.1$ ns. The time constant associated with trapping of photogenerated electrons at the surface varied between the samples with different surface treatments and the values are displayed in Table I. The Si$_3$N$_4$ SP GaAs sample showed the longest surface trapping time with a time constant $\tau$ of $167 \pm 2$ ps, significantly longer than the time constant of the untreated GaAs sample ($104 \pm 1$ ps). The increased trapping time indicates a successful reduction of the density of electron trapping states at the surface.

The surface-passivated sample without the Si$_3$N$_4$ encapsulation degraded in the weeks following passivation (the other samples were stable). This degradation is associated with a reduction in the surface trapping time constant and was thus easily observed. Three hundred and eleven days after the SP procedure, the surface-trapping time had stabilized to a value of $116 \pm 1$ ps. This value is significantly shorter than that of the encapsulated sample and is close to that of untreated GaAs ($104 \pm 1$ ps).

Table I

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\tau$ (ps)</th>
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<tbody>
<tr>
<td>Si$_3$N$_4$ SP GaAs</td>
<td>$167 \pm 2$</td>
</tr>
<tr>
<td>SP GaAs</td>
<td>$116 \pm 3$</td>
</tr>
<tr>
<td>GaAs</td>
<td>$106 \pm 1$</td>
</tr>
</tbody>
</table>

Therefore, while (NH$_4$)$_2$S is effective at passivating the surface of GaAs, and hence, reducing the density of trapping sites for electrons, its effectiveness degrades over a period of months after treatment. However, by encapsulating the treated surface with Si$_3$N$_4$, the passivation effect is retained in the long term. Thus, the passivation and encapsulation process shows great promise for use in device fabrication.

V. PCS CHARACTERIZATION

The THz radiation generated from the passivated and encapsulated PCSs was characterized with an average incident power of the laser beam of 160 mW. The detector crystal used was a 0.2 mm (110) ZnTe crystal on a 6 mm substrate of (100) ZnTe.

The emitted THz radiation pulses are shown in Fig. 3 for antennas fabricated on Si$_3$N$_4$ SP GaAs, SP GaAs, and untreated GaAs. Once again, the Si$_3$N$_4$ SP GaAs demonstrates the largest electric field amplitude (see Fig. 3), with a spectrally integrated power that is $4.1 \times$ that of GaAs. This may be attributed to the enhanced photoconductivity of the passivated and encapsulated material (see Fig. 2).

In the far-field approximation, the THz radiation pulse emitted from a photoconductive antenna has an electric field given by [18]

$$E_{THz} \propto \frac{1}{1 + \sqrt{\epsilon}} \frac{\partial J}{\partial t}$$

(1)
where the current density within a semiconductor under an applied field $\mathbf{E}$ is $\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_s$. The contribution of the diffusion current density $\mathbf{J}_d$ can be neglected on the timescales of THz emission ($\sim 1 \text{ ps}$). Further postulating that $\epsilon \neq \epsilon(t)$ one finds that $E_{THz}(t) \propto \partial J / \partial t = \partial (\sigma E) / \partial t$. The applied field $E$ between the contacts of a PCS is rapidly screened by the formation of the radiating dipole, an effect, which can be modeled quantitatively by Monte Carlo simulations incorporating the 3-D solution of Poisson’s equation [19]. Neglecting field-screening effects results in the prediction that $E_{THz}(t) \propto E \sigma / \partial t \propto \Delta \sigma / \Delta t$ if the photocconductivity rises within a certain time $\Delta t$.

The peak photocconductivity as measured in the OPTP experiments for the encapsulated and passivated sample was $1.4 \times$ greater than that of the pristine reference sample (see Fig. 2); however, the observed emission strength was $2.2 \times$ higher. This discrepancy may be a result of the photocconductivity rise time $\Delta t$ altering on a faster timescale than our experimental resolution for OPTP. Such effects can be examined with time-domain spectroscopy in the mid-IR, which also allows $\epsilon(t)$ on subpicosecond timescales to be investigated [20].

The necessity of the encapsulation layer in protecting the passivated GaAs can be seen in Fig. 3(b). There, the emitted THz pulse from a pristine SP GaAs emitter (made from a pristine GaAs emitter by passivating in 20% (NH$_4$)$_2$S for 10 min) is compared with that of a 117-day-old SP GaAs PCS. The new SP GaAs emitter has an electric field amplitude $1.8 \times$ that of the old SP GaAs emitter. The encapsulated SP GaAs PCS has a peak $E_{THz}$ [see Fig. 3(a)] that is $1.36 \times$ larger than the new SP PCS, because of the reduced reflectivity of the Si$_3$N$_4$-coated material.

VI. CONCLUSION

We have investigated the influence of SP and encapsulation on the performance of THz emitters based on SI GaAs. An Si$_3$N$_4$ overcoating layer on surface-passivated GaAs was found to enhance the conductivity of the material, and to prevent oxidation of the PCS surface that would otherwise degrade performance over a timescale of many days. Possible further work includes assessing whether passivation enhances the conductivity of low-temperature grown or ion-implanted GaAs, such as commonly used in photoconductive detectors of THz radiation.

REFERENCES


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