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ABSTRACT

There is a demand for more efficient sources of electromagnetic radiation in the terahertz (THz, $10^{12}$ Hz) frequency region. One common method of generating THz-frequency radiation is to direct fs pulses of near-infrared laser radiation onto a material which then re-radiates. This approach permits coherent pulses of THz radiation to be produced which, for example, may be used for time-domain spectroscopy (TDS). There are three principal mechanisms by which THz radiation is generated under the stimulus of ultra-short pulses: optical rectification (OR) in electro-optic materials, photoconductivity (PC) from materials with suitable electrodes, and surface-field (SF) effects in other cases. The III-V compound semiconductor GaAs doped with the acceptor impurity Be produces relatively small amounts of THz radiation via the OR and SF mechanisms, but relatively large amounts via the PC mechanism. We have studied the PC emission of THz radiation from layers of GaAs(Be) grown epitaxially on GaAs substrates. The THz power generated depends on the bias applied to the electrodes approximately quadratically. This is typical of the PC mechanism. The dependence of the THz power on the power of the pump beam is approximately linear. In general, the THz generated tends to decrease as the doping level increases. If the doping level exceeds the Mott limit and the material becomes highly conductive then the photoconductivity and consequently the THz production are quenched.

Keywords: THz, terahertz, emitter, semiconductor, gallium arsenide, GaAs, p-GaAs, GaAs(Be), GaAs:Be

1. INTRODUCTION

The region of the electromagnetic spectrum that lies between radio waves and visible light, some times referred to as “the THz gap”, is the subject of intense investigation at present. Materials for THz science and technology have been reviewed by Ferguson and Zhang. THz technology has been reviewed by Siegel. An outstanding problem is to develop more efficient emitters of THz radiation.

Of the various methods to generate THz radiation, the use of sub-ps pulses of near-infrared laser light is of particular interest, as the coherent THz pulses produced may be exploited in time-domain spectroscopy (TDS). The most common emitters used are semiconductors, such as ZnTe, which is an electro-optic material that exhibits optical rectification (OR) in transmission and p-InAs, which is a strong emitter in reflection. In this paper we concentrate on the compound semiconductor GaAs. Emission from GaAs in the absence of an applied electric field has been studied as a function of magnetic field and as a function of excitation optical fluence. With an applied electric field, GaAs becomes an effective photoconductive (PC) emitter. In particular, annealed, low-temperature–grown GaAs (LTG-GaAs) has been shown to be a strong THz emitter, operating over a wide range of frequencies.

In the work to be reported here we investigate GaAs intentionally doped with the acceptor Be as a candidate THz PC emitter. GaAs:Be has previously been the subject of extensive studies employing THz radiation. For instance, THz absorption spectroscopy has elucidated the hole energy levels. The low-temperature PC response has been investigated under the intense THz radiation provided by a free-electron laser (FEL). The
low-temperature PC response coupled with thermal excitation of holes into the valence band, a technique known as photo-thermal ionisation spectroscopy (PTIS), gives further information about the hole energy levels. Photoluminescence (PL) and photoluminescence excitation (PLE) studies have been conducted. Zeeman studies have been carried out in intermediate (up to 18 T) and high (up to 30 T) magnetic fields. LTG-GaAs:Be has been investigated using PC sampling. This has allowed electron and hole mobilities to be deduced.

A few studies have specifically considered GaAs:Be and related materials for THz emission. In this context the carrier lifetimes are important. The presence of free holes has been observed to increase lifetimes to the order of hundreds of picoseconds. Adding a layer of LTG-GaAs:Be has been shown to enhance the THz emission of undoped LTG-GaAs material. At low temperatures and under strong electric fields, strained GaAs:N:Be layers emit THz radiation.

### 2. EXPERIMENTAL METHODS

The eight samples investigated in this study were all grown at the University of Nottingham by molecular-beam epitaxy (MBE) on (100) semi-insulating GaAs substrates. The grown layers in each case are of micrometre dimension. Such thicknesses are not small enough to exhibit quantum confinement effects; in this sense the layers are “bulk”. Details of the layer thicknesses and the Be doping levels are provided in Table 1.

Electrodes were furnished on the samples by three different methods: gold-alloy evaporative coating, sputtering gold, and applying silver paint. The first method gave good results but is rather time consuming. The second method did not provide good adhesion of the metal to the sample surface; this is being investigated further. The third method is very simple and has provided good results previously when used on semi-insulating GaAs. This is the method for fabricating electrodes used in all the experiments to be reported here.

We first characterise the samples by measuring the current-voltage ($I$-$V$) curves without optical excitation from the near-infrared laser. The bias is supplied, and the resulting current measured, by a Keithley 2400 SourceMeter. Next, we characterise the samples by measuring the PC. To do this, we measure the $I$-$V$ curves under optical excitation. The optical excitation is by ultrashort pulses from a FemtoSource mode-locked Ti:sapphire laser. The pulse length is <12 fs, the centre wavelength 790 nm, the repetition rate 75 MHz. The optical power incident on the samples was restricted to below 350 mW to prevent damage to them. Focussing lenses of 10 cm or 20 cm focal lengths were used.

Sufficient THz radiation was produced in these experiments to be detected by a room-temperature pneumatic Golay cell (Pye Unicam SP50). The excitation beam was mechanically chopped at 11 Hz to permit synchronous detection with a lock-in amplifier (SRS SR830).

### 3. RESULTS AND DISCUSSION

Data for the least-heavily doped material, NU651, furnished with evaporated Au alloy contacts, has been presented elsewhere. It is similar to the data for the other samples to be presented here, and so will not be discussed further.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness ($\mu$m)</th>
<th>Be concentration (atoms cm$^{-3}$)</th>
<th>Be areal density (atoms cm$^{-2}$)</th>
<th>THz emission?</th>
</tr>
</thead>
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<tr>
<td>NU651</td>
<td>4</td>
<td>$1.5 \times 10^{15}$</td>
<td>$6.0 \times 10^{11}$</td>
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<tr>
<td>NU1444</td>
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</tr>
<tr>
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<td>$5 \times 10^{12}$</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>$1.5 \times 10^{13}$</td>
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</tr>
<tr>
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<td>$4 \times 10^{13}$</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>1</td>
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<td>$2 \times 10^{14}$</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 1. Details of GaAs:Be layers epitaxially grown on GaAs substrates
Figure 1. Data for NU1444. (a) $I-V$ characteristics with and without optical excitation, (b) Terahertz signal, as a function of applied bias.
The next most heavily doped sample is NU1444. Data for NU1444 is shown in Fig. 1. In Fig. 1(a) the $I-V$ curves are shown, both without and with optical excitation by the near-infrared laser. The effect of the optical excitation is to increase the current at a given applied bias, that is, to reduce the conductivity of the sample. In other words, the sample exhibits PC. The relative change in conductivity depends slightly on the bias voltage, and is in the range $7$–$13\%$ for the values of applied bias and optical excitation used here. In Fig. 1(b) the THz power is given as a function of the applied bias. More precisely, the response of the Golay detector is shown in mV on the vertical axis. We assume the Golay response is linear over this power range, so the Golay response should be directly proportional to the THz power generated by the sample. It is recognised that the conversion from Golay response to absolute THz power involves various difficulties and we do not attempt it here. The full lines in Fig. 1(b) are second-order polynomial fits to the data. It may be observed that the dependence of the THz power generated on the applied voltage is therefore quadratic. This dependence is characteristic of the PC mechanism. Data is given for two values of optical excitation power, $100$ mW and $256$ mW. Although this data is limited to only two powers, it is consistent with the THz power generated being directly proportional to the optical excitation power. Again, this dependence is typical of the PC mechanism. It may be seen from the upper right hand corner of Fig. 1(a), that the maximum electrical power applied to this sample in the present experiments was about $50 \text{ V} \times 10 \text{ mA} = 500$ mW. This is close to the limit of electrical power that could be supplied before joule heating would raise the temperature enough to reduce the resistance enough to cause thermal runaway. Likewise, increasing the optical power much above the values employed here would induce runaway, by lowering the resistance via the PC effect. Due to these considerations, not much more THz power can be produced from this sample than is illustrated in Fig. 1(b) unless cooling is arranged to remove this heat, as has been reported in other THz systems.

Preliminary results for sample NU2479 are shown in Fig. 2. Only one set of data is currently available, and that at a single optical excitation. The amount of THz radiation detected under these conditions is relatively small. It is thought that further refinement of the optical alignment of this sample will yield a greater THz power emission. Nonetheless, some general observations may be made from the data to hand. The PC response for this sample is similar to the last, amounting to about $10\%$ across the bias range used at the excitation power used. The THz power, as indicated by the Golay response, again follows an approximately quadratic dependence on bias, as indicated by the second-order polynomial fit in Fig. 2(b). The maximum electrical power supplied to this sample may be seen from Fig. 2(a) to be $\sim 150$ mW. This is well below the amount that could be applied before auxiliary cooling is required.

Figure 2. Data for NU2479. (a) $I-V$ characteristics with and without optical excitation, (b) Terahertz signal, as a function of applied bias.
Data for sample NU652 is given in Fig. 3. In Fig. 3(a) the $I-V$ curves are shown, both without and with optical excitation. The relative change in conductivity depends slightly on the bias voltage, but is typically 9% and always less than 10% for the optical excitation shown here. In Fig. 3(b) the THz power is given as a function of the applied bias. The dependence of the THz power generated on the applied voltage is quadratic. As with NU1444, at the maximum bias and the optical excitation used here, sample NU652 is close to the thermal runaway limit.

The electrical characteristics of sample NU1442 appear in Fig. 4(a). In contrast to the preceding samples discussed, NU1442 shows a very strong PC. Depending on the bias, the PC ranges from 50 to 150%. This is somewhat surprising, as this sample is more heavily doped, and so might be expected to have less scope to change in conductivity. However, the resistance of this sample, measured between the electrodes formed, is less than NU652, which also is somewhat surprising, given the relative levels of doping. The THz generation, shown in Fig. 4(b), again demonstrates a quadratic dependence on applied bias and a linear dependence on optical excitation power. As with NU1444 and NU652, this sample is close to thermal runaway under the experimental conditions employed.

The remaining samples – NU2568, NU650, NU1445 – were all highly conductive. Even at small bias, a large current flowed in these samples, leading to considerable joule heating. None showed a change in conductivity under laser illumination. None emitted any THz that could be measured. Comparing the most highly-doped THz emitter, NU1442, with the least highly-doped THz non-emitter, NU2568, we estimate the crossover from PC to metallic behaviour occurs at a Be concentration of $\sim 1.5 \times 10^{17}$ atoms cm$^{-3}$.

It is conceivable that incoherent sources of radiation are being detected in addition to the coherent THz radiation produced by the PC mechanism. For example, the excitation beam will lead to optical heating, which will be modulated at the chopping frequency, and so be susceptible to being detected in this experiment. Another possible source of incoherent radiation might be a component of the bias current fluctuating at the chopping frequency (even though the bias current itself is DC). Further, the DC bias current produces joule heating and so possible incoherent THz emission. To determine if such sources were interfering with our results, we operated the laser in continuous-wave (CW) mode. Under these conditions the signal detected by the Golay cell was negligible. We conclude mode-locked (ML) or pulsed operation is essential to the signal we detect, that is, all the radiation detected is being coherently generated.

4. CONCLUSION

We have observed that GaA:Be samples are emitters of THz radiation under pumping by ultrashort pulses of near-infrared radiation. The emitted THz radiation power varies quadratically with the applied bias and linearly with the incident optical power. We find that the amount of THz power produced decreases as the resistance of the sample decreases, or, generally speaking, decreases as the doping level increases. The most highly-doped material is the most efficient, in the sense of converting the greatest proportion of incident near-infrared radiation to THz radiation at a given applied bias. However, the least-highly doped material provides the highest absolute THz power, as it may be operated at a higher bias before thermal runaway occurs. Even higher powers of THz generation would be expected from all samples if external cooling were provided.

ACKNOWLEDGMENTS

This work was supported by the Australian Research Council.

REFERENCES


Figure 3. Data for NU652. (a) $I-V$ characteristics with and without optical excitation, (b) Terahertz signal, as a function of applied bias.
Figure 4. Data for NU1442. (a) $I-V$ characteristics with and without optical excitation, (b) Terahertz signal, as a function of applied bias.