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Investigation into free-space terahertz radiation from a LT-GaAs-on-quartz photoconductive emitter

David R. Bacon[1], Andrew D. Burnett[2], Matthew Swithenbank[1], Christopher Russell[1], Lianhe Li[1], Christopher D. Wood[1], John Cunningham[1], Edmund H. Linfield[1], A. Giles Davies[1], Paul Dean[1], and Joshua R. Freeman[1]

[1]School of Electronic and Electrical Engineering, University of Leeds, Woodhouse Lane, Leeds, LS9 2JT, United Kingdom

[2]School of Chemistry, University of Leeds, Woodhouse Lane, Leeds, LS9 2JT, United Kingdom

***Abstract* - We report on large-area photoconductive THz emitters and detectors with an LT-GaAs active region fabricated on quartz substrates using a lift-off transfer process. These devices are compared to the same LT-GaAs emitters when fabricated on the growth substrate. We find that the transferred devices show higher optical-to-THz conversion efficiencies and significantly larger breakdown fields.**

I. INTRODUCTION

We demonstrate high power free-space emission and sensitive detection of THz radiation using LT-GaAs transferred onto quartz substrates, a technique that has proven successful in on-chip THz waveguides [1]. While there are examples of free-space THz radiation emission from LT-GaAs bonded to sapphire [2], these do not provide a comprehensive comparison between lift-off-transfer devices and devices fabricated 'as-grown' on the SI-GaAs substrate, the latter of which are very widely used. Furthermore, here we focus on devices with large gaps, to produce high THz output fields and power.

II. EXPERIMENT AND RESULTS

In this work [3], we use Z-cut quartz as a substrate since it possesses a significantly higher electrical resistivity than SI-GaAs. It also exhibits low losses in the THz region, and is transparent to 800 nm light. Its low refractive index in the THz region of approximately 1.9 compared to 3.6 in SI-GaAs, is also a useful attribute in THz time-domain spectroscopy systems, as we demonstrate below. We fully characterize these emitters making use of two collection techniques. The first is a THz transmission geometry, in which optical excitation and THz collection occur on opposite sides of the device; the advantage of a low-index substrate here is that a smaller percentage of the THz pulse is reflected back into the substrate at the substrate-air interface, in comparison to when using SI-GaAs. In reflection geometry, however, excitation and collection occur on the same side of the device. In this orientation, a higher percentage of the generated signal should be emitted from the excited side, when compared with a device mounted on SI-GaAs. We first compare the emission properties of the newly fabricated LT-GaAs-on-Quartz (LoQ) devices with the transitionally used LT-GaAs-on-GaAs (LoG) device, in reflective geometry. The dependence of the peak-to-peak THz field on applied bias and optical power for both emitters is plotted in Fig. 1. At low applied fields, below 5 kV cm^{-1}, the response of the emitters is almost identical. As the field across the emitter is increased, the output signal from the LoQ device increases linearly to a maximum of 1 kV cm^{-1}, achieved at an operating applied field of 40 kV cm^{-1}. In comparison, the response of the LoG emitter was sub-linear until the device suffered catastrophic failure at an applied filed of 13 kV cm^{-1}. At the maximum operating voltage for each device, the LoQ device emitted approximately eight times higher peak THz field than the equivalent LoG emitter. The inset in Fig. 3 shows the detected THz field plotted as a function of optical power. Again, saturation behaviour is observed in the LoG device, while the response of the LoQ device remains almost linear. This unambiguously shows that the newly fabricated LoQ devices provide higher optical-to-

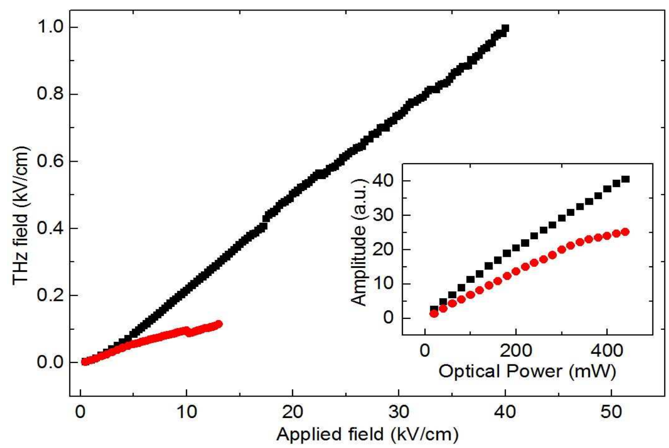

Fig. 1. Peak-to-peak value of the THz field, extracted from the time-domain signals, as a function of applied field. The inset shows the variation of peak-to-peak output amplitude with incident optical power. The black curve represents the quartz substrate and the red curve represents the SI-GaAs substrate.

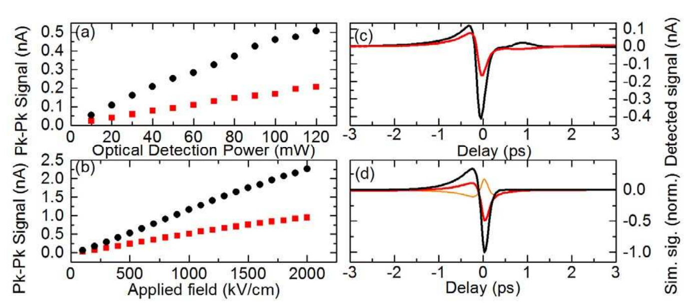

Fig. 2. Detected photo-current as a function of (a): the average optical excitation power focused on the detector and (b): the field applied to the emitter. (c): Detected time-domain signals from both devices. (d): Simulation results of time-domain traces for both detectors. The orange curve shows the contribution from the SI-GaAs substrate. In all instances, the LoQ detector is represented by the black line, while that on Si-GaAs in the red line.

THz conversion efficiencies and significantly larger breakdown fields when compared to SI-GaAs devices, which we attribute to reduced parasitic current in the substrate. This avoids current induced heating within the LoQ device, which is known to be detrimental to the efficiency of photoconductive emitters.

In addition to PC emission, the LoQ and LoG devices were also characterised as PC detectors. For comparison, a single LoQ emitter was used as the THz source for both detectors. Fig. 2(a) shows the peak-to-peak signal measured as a function of incident optical power focused onto the detector, and Fig. 2(b) shows the peak-to-peak signal as a function of bias applied to the emitter. In both instances, the peak field measured from the LoQ detector was more than twice that measured with the LoG detector. Fig. 2(c) shows the THz time-domain pulses detected from both devices. As can be seen, the LoQ detector shows a significantly larger second (negative) peak when compared with the trace from the LoG detector. This feature suggests that the SI-GaAs in the LoG device has a detrimental effect on its detection sensitivity. Through simulations based on coupled differential equations[4], the results of which are shown in Fig. 2(d), we determined that the reduction in detected current measured for the LoG device relative to the LoQ device is due to space-charge effects in the SI-GaAs substrate. Due to the longer momentum scattering time (higher mobility) in the SI-GaAs, the space-charge builds up more quickly in this layer. This amounts to screening of the THz pulse, particularly the second peak, in the SI-GaAs substrate that leads to a current acting in the opposite direction to the photo-current in the LT-GaAs layer, reducing the overall measured current.

To further compare the performance of emitters and detectors under investigation in this work with the performance of a more conventional THz-TDS system, we have plotted normalised time-domain traces in Fig. 3. THz radiation was collected in a reflection geometry. The red curve shows the response of the conventional TDS arrangement, employing a LoG emitter and electro-optic sampling for detection. This response shows four separate system reflections; as labelled, those occurring at 5, 10 and 17.5 ps originate from the 150-μm-thick electro-optic crystal, whereas the largest system reflection, arriving at 12.5 ps, originates from the 500-μm-thick SI-GaAs emitter substrate. The black trace shows the response when both emitter and detector are replaced with LoQ devices (with 2-mm-thick quartz substrates). In this case the first system reflection arrives 30 ps after the original pulse, originating from the interface between the air and the 2-mm-thick Z-cut quartz substrate. Owing to smaller contrast in refractive index between quartz and air, compared to SI-GaAs and air, this reflection appears significantly smaller in the LoQ-based system. This reduction in system reflections increases the available frequency resolution of the system without the need for post-processing techniques [5]. The inset to Fig. 3 displays the corresponding fast Fourier transforms of the time-domain traces, normalised to the noise in each case. In addition to the significantly greater SNR obtained from the LoQ devices, a smoother frequency-domain response, caused by the reduction in system reflections, is also evident. In this instance, we are able to perform a scan of delay six-times longer before the first reflection is recorded, resulting in a six-fold improvement in frequency resolution.

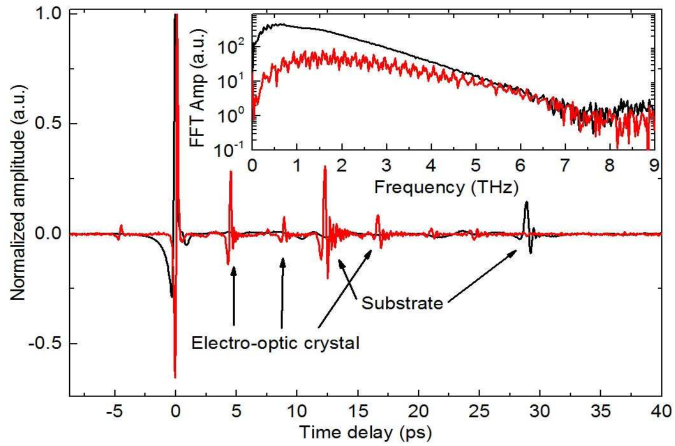

Fig. 3. Normalized time-domain trace using SI-GaAs substrate emitter with 150-μm-thick GaP electro-optic detection crystal (red line) and quartz substrate devices for both emitter and detector (black line). THz radiation was collected in a reflection geometry in both cases. Inset: FFT of the same data, normalized to the noise level.

III. Conclusion

In conclusion, epitaxial lift-off and van der Waals bonding techniques have been used to transfer LT-GaAs active layers onto quartz substrates, realising an alternative layered material combination for large-area THz photo-conductive emitters and detectors. It has been shown that these devices have three significant advantages over more widely-used PC emitters and detectors. The reduction in dark current and parasitic photo-current in quartz-based devices leads to reduced heating and increased breakdown voltages, resulting in THz field amplitudes approximately eight-times larger than those obtained from equivalent devices formed using LT-GaAs on SI-GaAs substrates. When used for PC detection the absence of an SI-GaAs substrate also eliminates the long-lifetime carriers and increases the measured signal. Furthermore, the ability to choose a thicker substrate allows system reflections to be delayed in time and their amplitude to be reduced without a loss of bandwidth, thereby increasing the available frequency resolution.

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