

Ultrabroadband terahertz pulses from a Ge:Au photoconductive emitter

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Abstract

Using gold-implanted germanium, where the carrier lifetime is shortened by more than three orders of magnitude, we have demonstrated a broadband photoconductive THz emitter compatible with modelocked fiber lasers operating at wavelengths of 1.1 and 1.55 μm and pulse repetition rates up to 20 MHz. The emitted THz spectrum spans up to 70 THz. This approach opens up a prospect for manufacturing of compact, high-bandwidth THz photonic devices compatible with Si CMOS technology.

1. Introduction

Germanium is a nonpolar semiconductor with missing one-phonon absorption. The absence of a Reststrahlen band enables the generation of a gapless THz spectrum spreading up to 13 THz [1], limited only by the duration of the excitation and detection laser pulses. However, in spite of other promising properties including low bandgap and small effective mass, the long, μs -scale recombination time arising from the indirect bandgap of intrinsic germanium has been prohibitive for practical application as photoconductive THz emitters. Although not essential for broadband THz emission, shorter recombination times are necessary to ensure complete carrier recombination between subsequent laser pulses and to make these emitters compatible with standard modelocked laser systems operating at pulse repetition rates up to hundreds of MHz.

2. Results

In order to make Ge a suitable photoconductive material at MHz repetition rates, we have reduced the carrier lifetime by introducing deep traps via Au implantation. Although a shorter carrier lifetime is not an essential requirement for the broadband THz emission, sub-ns lifetime ensures reliable operation of Ge:Au THz emitters at repetition rates up to few 100 MHz covering specifications of most contemporary femtosecond oscillators. Ge substrates were implanted with Au ions with energy of 330 keV and doses

of $\approx 2 \times 10^{13}$ ions/cm² followed by annealing at 900 °C for several hours in order to ensure a low homogeneous concentration of gold impurities near the surface of the Ge wafer. The achieved doping density is approximately 10^{15} cm⁻³.

The carrier lifetime in implanted Ge:Au wafers were measured using optical pump / THz probe spectroscopy. We observe a strong photoconductivity decay within 1 ns after photoexcitation and a negligible offset at negative delay times. The longest measured recombination time of 1.7 ns is more than 1000 times shorter than in an undoped Ge, where it reaches several μs .

Bowtie electrode structure was fabricated using the same fabrication process and the bowtie electrode geometry as our previous work [1]. The near-infrared pump beam is focused onto the 10- μm -gap between the electrodes. Photoexcited charge carriers are accelerated by the applied bias field (d.c. bias voltage of 10 V) producing a transient current burst. The THz beam emitted by this current in forward direction is collimated and refocused on an electro-optic crystal for field-resolved detection.

THz emission was induced by 11 fs pulses with a central wavelength around 1.1 μm (spectrum spanning from 0.9 to 1.25 μm) and an energy of 7 nJ. The generated THz transient is detected by electro-optic sampling using 8.42-fs-short probe pulses in a (110) ZnTe crystal with a thickness of 14.3 μm . Fig. 1(a) shows the recorded THz electric field in the time domain. The pulse duration comprises about 1.5 optical cycles and the estimated peak electric field in the focus reaches 0.8 kV/cm [2]. Fig. 1(b) depicts the Fourier spectrum of the THz transient spanning from the lowest detectable frequency up to 70 THz. The small dip in the spectrum at around 5 THz is caused by the response function of the ZnTe detector and the true THz emission spectrum is gapless as it has been confirmed in previous work [1].

Furthermore, we demonstrated the compatibility of the Ge:Au photoconductive antenna with the conventional telecom wavelength of 1.55 μm covered by ubiquitous Er-doped femtosecond fiber lasers. The absorption edge of Ge

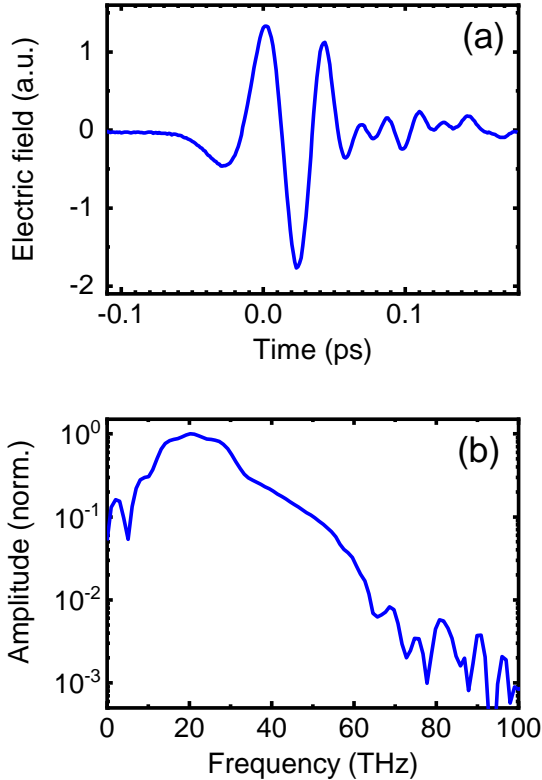


Figure 1: (a) Recorded THz pulse for pumping with 11 fs pulses centered at 1.1 μm wavelength. (b) Fourier transform of the recorded THz pulse.

at 1.87 μm is well below the telecom band. However, due to the indirect bandgap the absorption is rather weak and increases abruptly only for wavelengths shorter than 1.55 μm , for which the direct interband transitions are allowed. The photoconductive antenna was pumped with 12 fs pulses with a central wavelength around 1.55 μm and the energy of 3.5 nJ at the repetition rate of 20 MHz. The resulting THz spectrum (not shown) spans up to 50 THz demonstrating that the Ge-based photoconductive antenna is capable for broadband THz emission when pumped at telecom wavelength [2].

3. Conclusions

We have demonstrated a photoconductive THz emitter based on ion implanted germanium that generates THz transients with a gapless spectral coverage up to 70 THz – a full order of magnitude larger than existing GaAs or InGaAs-based devices. Implantation of gold ions enables us to reduce the carrier lifetime down to the nanosecond level, rendering the new device compatible with high repetition rates of femtosecond fiber lasers. Owing to the relatively low bandgap energy of germanium, it can be photoexcited using the conventional telecom band wavelengths. In our experiments we demonstrate broadband THz emission under excitation by few-cycle pulses at central wavelengths of 1.1 and 1.55 μm , produced by state-of-the-art amplified

Er:fiber laser systems. Potentially, Ge-based THz devices can revolutionize THz technology due to its ultrabroad spectral bandwidth coverage and its compatibility with Si CMOS technology.

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