Terahertz time-domain spectroscopy system based on femtosecond Yb:KGW laser


The terahertz time-domain spectroscopy system using 1030 nm wavelength femtosecond pulses generated by a Yb:KGW laser is presented. The system, employing p-InAs crystal as the emitter and GaBiAs dipole antenna as the detector, has reached the spectral width of more than 2 THz and the signal-to-noise power ratio of ~60 dB.

Introduction: In the past decade, the methods of generation and coherent detection of ultra-short electromagnetic pulses with a spectral content from 0.1 to 10 THz (THz pulses) have evolved as a useful tool for many attractive applications [1]. Most effective of these methods, i.e. those using ultrafast optoelectronic semiconductor switches for the detection of THz pulses, require femtosecond pulse lasers and a material with subpicosecond carrier lifetime photosensitive at the laser wavelength. As yet, the majority of terahertz time-domain spectroscopy (THz-TDS) systems are based on femtosecond Ti:sapphire lasers (wavelength of ~800 nm) and low-temperature-grown (LTG) GaAs switches. Most recently, more efficient and cost-effective solid-state and fibre laser systems that are directly diode-laser pumped and generating femtosecond pulses at longer wavelengths from 1 to 1.5 µm have been developed [2, 3]. THz pulse emission can be readily obtained by illuminating narrow-gap semiconductors, such as InAs surfaces, whereas its detection in long-wavelength laser activated systems is more complicated. The absorption edge of GaAs is at ~0.9 µm, thus this material is not suitable for devices activated by longer wavelength lasers. Longer wavelengths can be reached with InGaAs, however LTG or ion-implanted InGaAs layers have low resistivity, which is a serious obstacle for the photodetector applications. Detectors made from Fe-ion-implanted InGaAs were used in a THz-TDS system activated by 1560 nm wavelength pulses in [4]; signal-to-noise ratio of only ~100 was achieved and the detectors were unstable at higher optical excitation densities. The THz-TDS system based on LTG GaAsSb devices has a bandwidth not exceeding 1 THz [5]. In our previous work [6], growth and characterisation of another ternary compound, GaBiAs, was reported. The LTG GaBiAs layers had rather large resistivities and shorter than 1 ps electron lifetimes. Here we describe their use in ultrafast photoconductive switches for a THz-TDS system activated by 1 µm wavelength laser pulses.

Experimental details: An epitaxial GaBi0.05As0.95 layer was grown on semi-insulating (100)-oriented GaAs substrate in a solid-state molecular-beam-epitaxy (MBE) system at 300°C substrate temperature at the growth rate of 2 µm/h. The thickness of the layer was 400 nm; beneath it an LTG GaAs buffer layer of the same thickness was grown. The optical absorption edge of the GaBi0.05As0.95 layer was at 1200 nm; its resistivity 20 Ωcm. This layer was used for manufacturing a Hertzian dipole antenna with a 15 µm-wide photoconducting gap. Antennae were equipped with substrate lenses from semi-insulating GaAs crystal and were used both as THz emitters and as THz detectors. Laser excited surfaces of different semiconductor materials as the sources of THz radiation were also investigated.

A femtosecond laser was the oscillator from the high repetition rate femtosecond system Pharos from Light Conversion Ltd. The oscillator was based on directly diode pumped Yb:KGW (KGaWO4) crystal. Kerr-lens mode locking was used to generate optical pulses with the central wavelength of 1030 nm. The average output power of the oscillator was 600 mW, the pulse duration was 63 fs (Gaussian fit), the spectral width (FWHM) was 28 nm, and the pulse repetition rate was 75 MHz.

Results: Various THz emitters and a GaBiAs photoconductive detector were tested in a standard THz-TDS setup [7]. Fig. 1 shows THz pulse measured in a quasi-reflection direction from the emitter which was a THz field amplitude, a.u.

Fig. 1 THz pulse generated in TDS system consisting of p-InAs emitter and LTG GaBiAs detector

Fig. 2 Fast-Fourier transform spectrum of THz pulse shown in Fig. 1

Fig. 3 Amplitude of THz pulses generated by laser excited surfaces of InxGa1-xAs crystals with different composition energy against bandgap

Vertical dotted line marks laser photon energy optimising the material technology. The surfaces of other investigated semiconductors, including n-type InAs crystal, were far worse THz emitters than p-InAs. Results of these investigations are summarised in Fig. 3, where THz-field amplitude emitted at the same experimental conditions from various materials is plotted against energy bandgap of the semiconductor. It is interesting that THz radiation from the surface of different InxGa1-xAs compounds was observed even when the energy bandgap of the compound became larger than the exciting photon energy. This experimental observation, as well as the fact that p-InAs is a better emitter than n-InAs, indicates the prevalence of nonlinear optical interaction as the main mechanism of THz radiation from these materials [8].

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Photoconductive antennae made from LTG GaBiAs were also used as THz emitters in the TDS system, however, due to the limited DC voltage that could be applied for their bias, the THz field amplitude was smaller than that of the p-InAs surface emitter. This limitation could possibly be overcome by optimisation of the emitter geometry, which is under way presently.

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