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New Performance Limits of an Ultrafast THz Photoconductive Receiver

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Common to all recently demonstrated optoelectronic sources of pulsed THz radiation has been the problem to properly characterize the source with receivers of limited bandwidths. To date the broadest bandwidth receiver has used ion-implanted, silicon-on-sapphire (SOS), photoconductive switches (1). Here, we report a new type photoconductive receiver with a measured response exceeding 6 THz. This receiver uses a new composite optoelectronic chip (shown in Fig. 1a) consisting of an active layer of ion-implanted polysilicon on top of a thick thermal oxide on a high-resistivity silicon substrate. By using as the transmitter an identical receiver in a high-performance optoelectronic THz beam system, we were able to characterize the receiver with exceptional precision. Excellent agreement with a Drude theory model for the photoconductive response was obtained.

The antenna structure shown in Fig. 1b is used for both the receiver and the transmitter, for which a bias voltage replaces the current amplifier. The structure is embedded in a coplanar transmission line consisting of two parallel 5-μm-wide aluminum lines separated by 10 μm. The operation is based on the creation of photocarriers in the electric field in the gap between the two arms of the antenna. A colliding-pulse mode-locked (CPM) dye laser provides the 5 mW focused beam of 623 nm, 80 fsec excitation pulses. As illustrated in Fig. 1c, the THz radiation from the source chip is collected and collimated by the silicon lens attached to the back-side of the chip. The resultant diffraction limited beam of pulses of THz radiation is

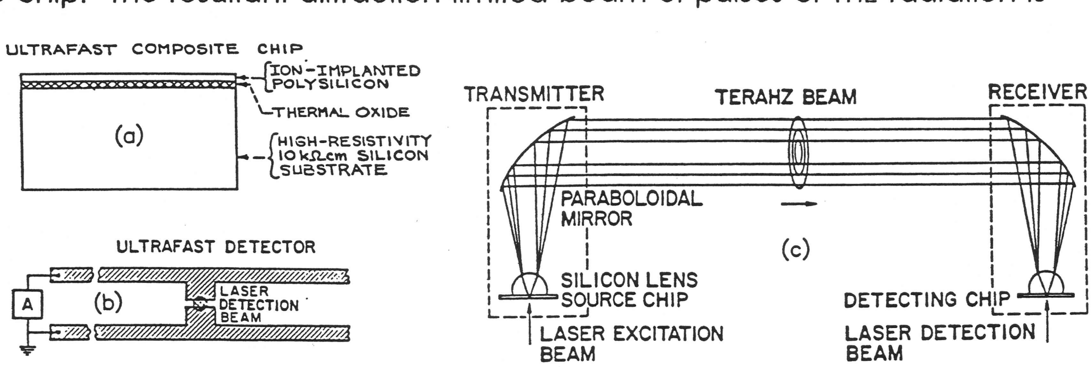

Fig.1 (a) Cross-section of the composite-chip. (b) Receiving and transmitting antenna structure. (c) THz collimating and focusing optics.

recollimated by a paraboloidal mirror. The THz beam incident upon the receiver is focused by a second matched paraboloidal mirror onto a second silicon lens, which in turn focuses it onto the receiving antenna.

Using this receiver, we now measure a source spectrum with a FWHM bandwidth almost twice as broad as the initial experimental characterization of a similar system using SOS chips (1). The improved performance is due to the following changes. Firstly, the positions of the paraboloidal mirrors were set to have a unity transfer function for the THz radiation. Secondly, exceptional care was taken to match the foci of the silicon lenses to the antenna positions. For the on-axis focusing a series of observations were made using lenses of the same curvature, but with thicknesses varying in steps of 50 μm. In the plane of the chip the position of the focus was adjusted to +/- 20 microns. Thirdly, as shown in Fig. 1a, a new composite-chip was used to eliminate the absorption of the incoming THz radiation by the sapphire substrate of the previously used SOS detection chip. The 0.5 μm-thick active layer of LPCVD polysilicon of the composite chip was annealed at 1000 degrees C for 1 hour in a nitrogen atmosphere and was later implanted with 200 keV and 100 keV oxygen ions both at a dose of $10^{13}/cm^2$. The 0.7 μm-thick thermal oxide layer was grown on a high resistivity silicon substrate.

The THz pulse measured with the ultrafast receiver is shown in Fig. 2a. The fall-time (90%-10%) from the peak of the pulse to the minimum is only 127 fsec, as shown in the expanded view of Fig. 2b. This exceptional time resolution demonstrates that a photoconductive receiver can be much faster than is generally realized, but is consistent with the earlier prediction (for SOS chips) of a 150 fsec time resolution (1). The numerical Fourier transform of this pulse peaks at approximately 0.5 THz and extends

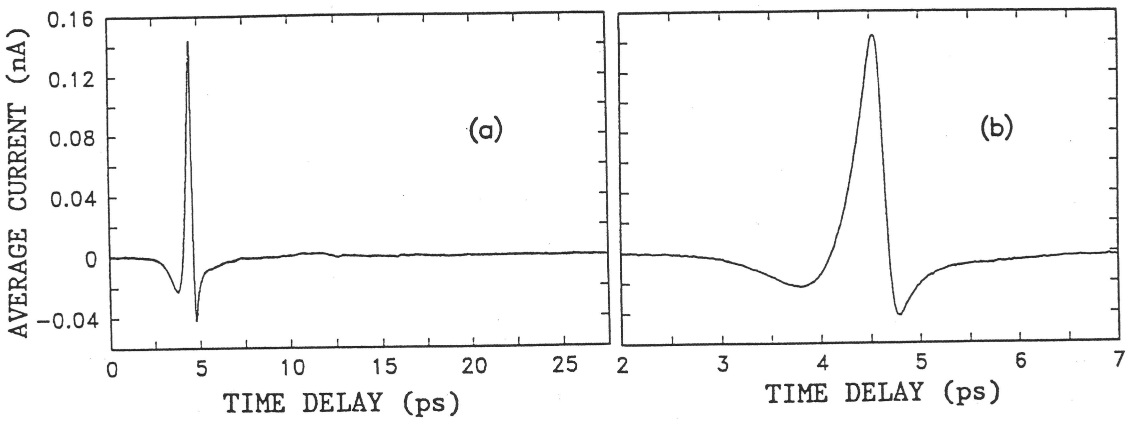

Fig.2 (a) THz pulse measured by the ultrafast receiver. (b) Measured THz pulse on an expanded time scale.

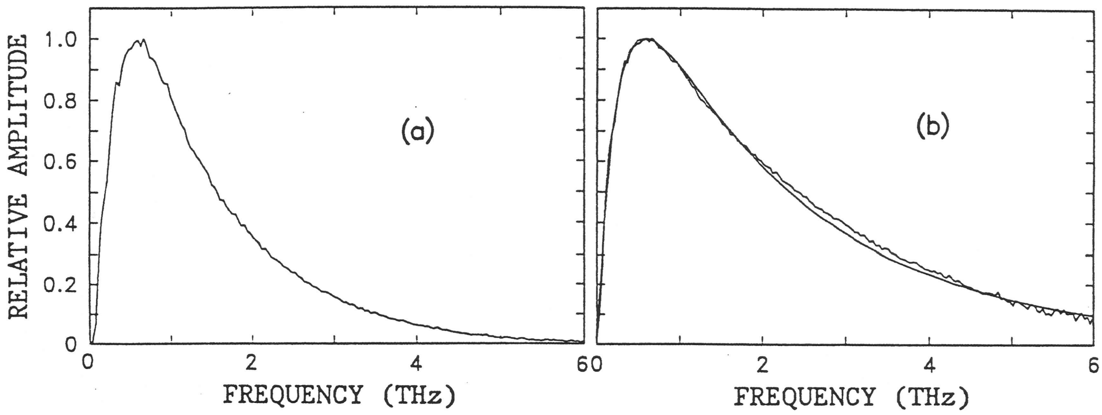

Fig.3 (a) The numerical Fourier transform of Fig. 2a, equal to the receiver power spectrum. (b) Comparison of the calculated receiver amplitude spectrum with the measured amplitude spectrum (square root of Fig. 3a).

to 6 THz, as shown in Fig. 3a. The measured spectrum is the product of the transmitter and receiver amplitude spectra. However, because here the transmitter and receiver are identical, the receiver amplitude spectrum shown in Fig. 3b is simply the square root of the measured spectrum of Fig. 3a.

Because of the extremely fast electrical response, the current in the ultrafast antenna follows the current J(t) in the semiconductor, where J(t) is determined by the convolution of the photoconductive response function and the 80 fsec (FWHM) $sech^2$-shaped laser driving pulse. Following the theoretical procedure of Ref.(1), the response function is derived from simple Drude theory with a scattering time of 120 fsec and a carrier lifetime of 600 fsec. The receiver response is obtained by considering a transmitter in the small antenna limit corresponding to the Hertzian dipole, for which the generated radiation field is proportional to the time-derivative of the J(t). Evaluation of this time-derivative shows that the Hertzian dipole antenna generates a 150 fsec FWHM pulse of THz radiation. Conversely, by the reciprocity principle, 150 fsec is also the time resolution of the photoconductive receiver. The corresponding amplitude spectrum for the receiver is shown in Fig. 3b. The excellent agreement with experiment shows that, to a very good approximation, the semiconductor response follows Drude theory and that the resulting response time is limited by the ballistic acceleration of the photocarriers.

1. D. Grischkowsky and N. Katzenellenbogen, Proc. of the Psec. Elect. and Optoelect. Conf., Salt Lake City, Utah, March 13-15, 1991, T.C.L. Gerhard Sollner and Jagdeep Shah, Eds. (Opt. Soc. of Am., Washington D.C. 1991), Vol.9, pp. 9-14.