High-performance terahertz electro-optic detector

J. Kröll, J. Darmo and K. Unterrainer

An electro-optic terahertz (THz) detector with a metallic antireflection coating is presented. The performance of this detector does not suffer from the reflection of THz radiation within the crystal. This enhances tremendously the resolution of THz time-domain spectroscopy.

Introduction: Recent progress in terahertz technology has shown the huge potential of electro-optic detectors in terahertz time-domain spectroscopy [1–3]. The spectroscopic information is extracted from the time-domain signal by fast Fourier transformation. The validity of the obtained results depends strongly on the quality of the original time-domain signal. Owing to refractive index mismatch at the electro-optic crystal/air interface the signal trace contains multiple time delayed reflections of the main THz pulse. As known from Fourier algorithm theory, any reflection within the signal trace manifests itself as modulation of the original spectrum according to the expression

$$f(t) + kf(t-T) \xrightarrow{FFT} F(\omega) + kF(\omega)e^{j\omega T} \quad (1)$$

where $kf(t-T)$ is the reflected signal of the main signal $f(t)$. The amplitude of the modulation k is proportional to the amplitude of the reflection and the modulation frequency depends on the time delay T of the reflection. Such modulation disturbs significantly the information gained from the calculated spectrum, since spectrally narrow information can be hidden within.

At present the problem of THz pulse reflections in the electro-optic detector is solved by the use of thick electro-optic crystal substrates which, however, only postpone the reflection in time [4]. The reflections could be completely eliminated by the use of a dielectric quarter-wave-thick ($\lambda/4$) layer. However, this would require a layer thickness of several tens of microns for $\lambda = 100$–300 μm (~1–3 THz), and it would not work broadband enough for time-resolved measurements with ultrashort (sub-picosecond) pulses. Another possibility to eliminate the reflection at the crystal/air interface is to improve the impedance matching by a properly chosen thin conductive layer (i.e. a shunting resistor).

In this Letter we report on a broadband absorptive antireflection coating (MARC) that suppresses the reflection of terahertz pulses within an electro-optic detector (see Fig. 1). The antireflection coating is made of a thin chromium layer. We have applied THz time-domain spectroscopy to prove the layer functionality. We estimate for the first time the complex index of refraction of such layers in the spectral range 0.1–4 THz.

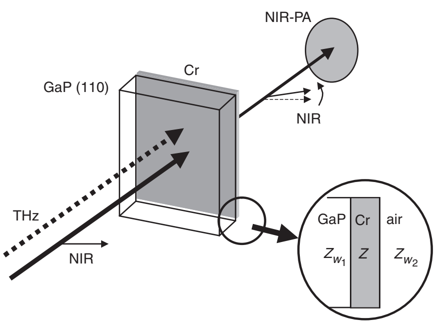

Fig. 1 *Schematic of detection of THz radiation by electro-optic sensor (GaP crystal of (110) orientation)*

THz electric field changes birefringence of crystal and thus polarisation of near-infrared beam, which is later detected
NIR-PA: NIR polarisation analyser

The reflection of an electromagnetic wave at the interface of two different optical media can be considered through the mismatch of their wave impedances. This allows us to model the interface as a junction of two transmission lines. To match their wave impedances, and hence to suppress the reflection at the junction, the theory of electrical circuits suggests the introduction of a shunting impedance between these transmission lines. Such shunting impedance Z has to satisfy the relation

$$Z = \left| \frac{Z_{W_2} Z_{W_1}}{Z_{W_2} - Z_{W_1}} \right| \quad (2)$$

where Z_{W_1} and Z_{W_2} are the wave impedance of the optical media. In practice, the shunting impedance can be realised by a metallic layer with a convenient resistivity and thickness. The sheet impedance Z of such layer, when the Drude model of metal's refractive index is adopted, can be expressed as [5]

$$|Z| = \frac{1}{d * \sigma_{DC}} * \sqrt{1 + \frac{\omega^2}{\beta^2}}$$

where d is metal layer thickness, σ_{DC} is metal low-frequency conductivity, and $1/\beta$ is the scattering time of the electrons in the metal.

Experiment: The material of choice for the antireflection layer can be any metal with medium conductivity σ_{DC}. Highly conductive metals like gold would require a deposition of a very thin layer to reach the layer's required sheet resistance $d{*}\sigma_{DC}$ (see (3)). That is, however, technically difficult to handle precisely enough. Another criterion for the material choice is long-term stability of the metal parameters. We have chosen chromium, which exhibits a conductivity about 5.7 times lower than that of gold. Other possible candidates are platinum, wolfram, iridium etc.

With respect to the generally known dependence of the material parameters (e.g. resistivity) of thin layers on the film's thickness, we have to estimate the optimal layer's thickness experimentally. Therefore, we have prepared a set of Cr layers of different thickness deposited on high-resistive silicon substrate. The layers were then evaluated by THz time-domain spectroscopy [6].

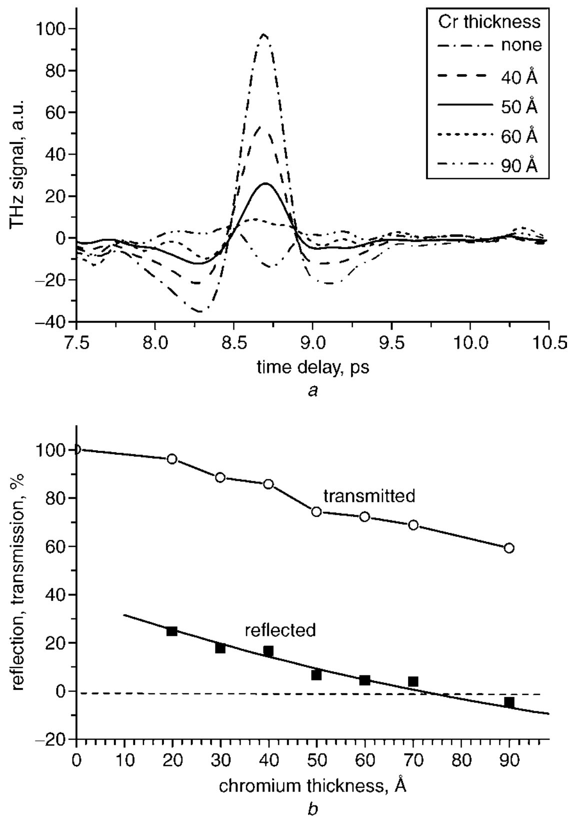

Fig. 2 *Reflection of THz pulses at silicon/Cr/air interface system*

a Time window where reflection appears (parameter—Cr layer thickness)
b Amplitude of reflected THz pulse against Cr layer thickness (solid line is theoretical fit)

Fig. 2*a* shows THz pulses reflected from the system silicon/Cr/air interface which appears about 8.7 ps after the main pulse. This time delay corresponds to a round trip of the THz pulse in the 400 μm-thick silicon substrate. We have corrected the amplitude of the pulses to account for the transmission and reflection losses at the silicon/air

interface. The amplitude of the reflected and transmitted pulses is decreasing for thicker Cr layer (Fig. 2*b*) because the sheet resistance of the layer is decreasing. For a layer of thickness of 90 Å, the amplitude of the reflected THz pulse becomes negative in full agreement with the theory [5]. By fitting the experimental data to the theoretical model we get an optimal thickness of the Cr antireflection layer of 77 Å. At this thickness the Cr layer absorbs about 62% of the THz radiation. The effective index of refraction n of the thin Cr layer in the frequency range 0.1–4 THz was estimated to be $n = 37 + I * 85$.

Finally, we have applied the MARC to a GaP electro-optic sensor. Fig. 3*a* shows the time-domain THz signal generated from a photoconductive THz emitter [7] measured by a 300 µm-thick (110) oriented GaP crystal without and with the metallic antireflection layer. In the reference time-domain signal, a reflected THz pulse within the GaP sensor appears 7 ps after the main pulse (Fig. 3*a*). The amplitude of the reflected pulse is about 22% of the main THz pulse. The application of the MARC reduces this reflection below 2%. The residual reflection in the signal is due to an uncertainty in the control of the thickness of Cr films during the deposition on the GaP crystal and can be further improved. The comparison of the spectral intensity of the transmitted and the reference THz pulses shows a flat frequency dependence of the MARC properties in the range 0.1–4 THz (see inset in Fig. 3*a*).

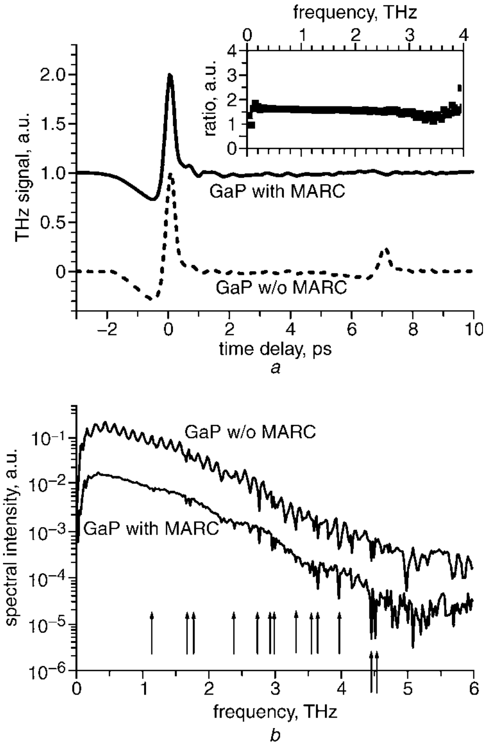

Fig. 3 *Comparison of THz signal measured by GaP electro-optic detector with and without chromium antireflection coating (MARC)*

a Time-domain data
Inset: Frequency dependence of MARC properties
b Frequency-domain data
Arrows indicate water absorption lines. Curves offset for clarity

The reduction of the reflection in the electro-optic crystal has a dramatic influence on the quality of the spectral data obtained by fast Fourier transformation of the time-domain signal (Fig. 3*b*). The narrow absorption lines at frequencies of 1.67, 1.71, 2.63, 2.78, 2.98, 3.01, 3.32, 3.65, 3.98, 4.51 and 4.6 THz (indicated by arrows in Fig. 3*b*) due to the residual water vapour [8] in the THz beam path are masked by a strong periodic modulation of the spectrum caused by the presence of a reflected pulse in the signal. However, the water vapour absorption lines are well distinguished when the MARC is employed.

Conclusions: An electro-optic THz detector with a chromium antireflection layer has been presented. The index of refraction of the thin Cr layer is effectively frequency independent in the THz frequency range 0.1–4 THz. Such a metallic layer can be successfully used as a broadband antireflection coating for electro-optic sensors of finite thickness and for a range of different applications in which suppressed reflection of THz radiation can be traded-off at the expense of partial absorption.

Acknowledgment: The authors acknowledge financial support from the Austrian Fonds zur Förderung des Wissenschaftlichen Forschung (SFB-ADLIS).

2 April 2004
Electronics Letters online no: 20040492
doi: 10.1049/el:20040492

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