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Large-area sub-micron gap interdigitated THz emitters fabricated by interference lithography and angle evaporation

K. Huska, G. Klatt, J. Hetterich, U. Geyer, T. Dekorsy, G. Bastian and U. Lemmer

Interference-lithography and a self-aligning angle-evaporation technique are employed to fabricate interdigitated photoconductive terahertz (THz) emitters. The devices have a large active area for high directivity and submicron spaced electrodes for high internal electric fields at low bias voltages. The fabrication process offers the advantage that only one patterning step is needed to generate three isolated metallic structures. This avoids critical alignment and reduces the fabrication effort significantly. Voltage dependent THz emission is observed from 4 V upwards.

Introduction: Electromagnetic waves with frequencies in the terahertz (THz) range have huge potential for applications in spectroscopic and imaging applications in materials science [1] and life sciences [2, 3]. Broadband THz sources providing enough intensity to achieve a high signal-to-noise-ratio are essential for these applications. Recently, the use of interdigitated photoconductive emitters excited by femtosecond lasers has been demonstrated for efficient THz generation [4, 5]. These emitters are based on a periodic arrangement of electrodes on a photoconductive material. These electrodes are arranged in a way that optical excitation with an ultrashort laser pulse takes place only in regions with uniform and unidirectional electric fields in the photoconductive substrate. These emitters have the advantage that large areas can be optically excited while high static electric fields are maintained [5]. This initial concept has been further developed in order to reduce and simplify the required process for these emitters [6, 7]. A straightforward extension of this concept is the use of submicron interdigitated structures (IDS). Interference lithography (IL) and angle evaporation are promising methods for the realisation of THz emitters since such devices allow for very high local fields as well as for large areas resulting in highly directed THz radiation in the far field.

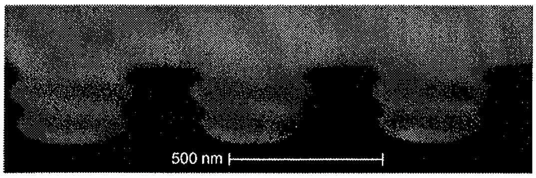

Fig. 1 *Electron beam micrograph of the resist-profile after interference lithography and development. Contrast was optimised to show the standing wave profile*

Fabrication principles: The interdigitated THz emitters require a periodic array of finger electrodes [4]. The photo-conductance between every second finger pair has to be suppressed since the change of the static electric field would lead to carrier acceleration with opposite directions. This carrier acceleration would result in destructive interference of the emitted THz radiation in the far-field. The fabrication of the shading [4, 5] or trenches [6, 7] between every second electrode requires an alignment of a second patterning step with respect to the first structure. This causes a major complexity for submicron structures on a large area. To overcome those difficulties a new concept based on IL and angle evaporation has been developed. The utilisation of the photoresist edge arising from the vertical standing wave patterns during IL (see Fig. 1) allows for the evaporation of electrodes without electrical connection between them. Figs. 2*a* and *b* show the underlying principle. The metal is evaporated into the trenches that does not result in shorts if the angle of incidence and layer thickness is chosen properly. By evaporating under two angles α_1 and α_2 it is possible to produce two electrodes and a gap between them into every trench defined in the resist by IL. The resulting opaque metallisation on the top of the resist profile is generated simultaneously. This layer is insulated from the electrically active IDS. Additional conventional photolithographic and thin film processes are used to define the outer electrodes and contact windows. Additional tilting of the substrate in the direction parallel to the grating in combination with two shadowing elements on the sample holder provides contact of the finger electrodes to the respective outer electrodes (Figs. 2*c* and *d*).

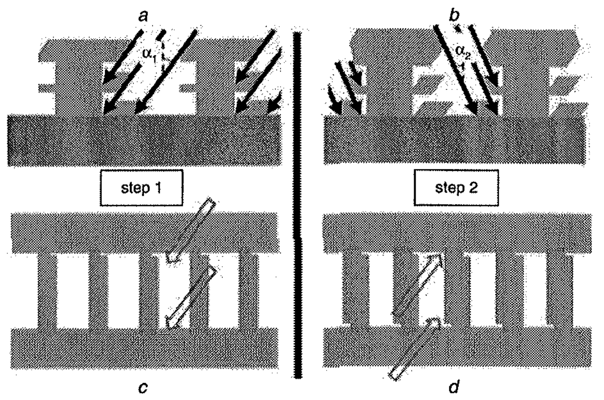

Fig. 2 *Scheme of the angle evaporation process. Step1: evaporation of the first set of fingers under the angle α_1 perpendicular to the grating. By tilting parallel to the grating by the angle β_1 and owing to the shadowing elements on the holder the respective outer electrode gets connected (c). Step 2: respective process for the second set of fingers using the angles α_2, β_2 (b, d). Top metallisation is generated simultaneously (not shown in c, d for clarity)*

Technology: Pieces of 18×22 mm^2 from a 4″ semi-insulating double side polished GaAs-wafer (VGF AXT™) were coated with a 200 nm layer of the positive tone photoresist (Ar-P 3170 AllResist™) by spin coating. The exposure was done by our IL setup consisting of an Ar-ion laser (Coherent Innova Sabre) working at a wavelength of 363.8 nm in singlemode. Before development, 2 mm wide windows were defined by conventional photolithography for contacting the side electrodes, which were evaporated before resist processing. The sample was fixed on a specially designed holder containing shadowing elements. Those elements, in combination with the tilt angles (β_1, β_2) perpendicular to the grating, enable the selective connection of the finger electrodes to the respective outer electrode (Fig. 2*c*). The sample was exposed to the evaporation source twice at the angle sets α_1, β_1 and α_2, β_2. The outer electrodes were contacted by copper strips. Fig. 3 shows an SEM image of the finalised emitter where light parts are the photoresist strips covered by metal (A), between them the two 150 nm wide electrodes (dark grey, B) spaced by about 100 nm gaps of uncovered GaAs (black, C). The *I-V* characteristics of the samples were measured by a source measurement unit (Keithley 238). Fig. 4 shows the *I-V* characteristics in the dark and under illumination. The photo response of the device is clearly visible.

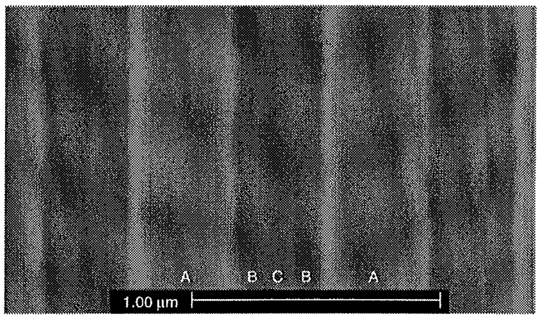

Fig. 3 *SEM image of an emitter after all process steps*

Brighter areas (A) are top metallisation on photoresist shading the underlying GaAs
Grey strips (B) are finger electrodes on GaAs surface
Dark areas (C) are uncovered GaAs where carriers are photo-excited

THz-measurement: The THz emission was investigated by time-domain THz spectroscopy using a system based on high-speed asynchronous optical sampling [8, 9]. The system provides a spectral sensitivity from 0.1–7 THz and high dynamic range without a mechanical delay line. The pump beam (300 μm spot diameter, 1×10^{16} cm^{-3} excitation density) excites the structured part of the emitter device, the THz radiation is emitted through the emitter substrate and is collected by parabolic mirrors on an electro-optic detection crystal. Fig. 5 shows the Fourier spectra for different bias voltages applied to the emitter, the inset shows the corresponding transients. The bandwidth of the emitters extends to 3 THz, the peak frequency is located slightly over 1 THz. For bias voltages smaller than 2 V, the THz radiation originating from the build-in electric field superposes the THz radiation resulting from the external bias field. The superlinear increase of the emitted THz radiation above 4 V results from the increasing contribution of carrier deceleration owing to side-valley transfer, which is suppressed at smaller fields and small electrode spacing [10].

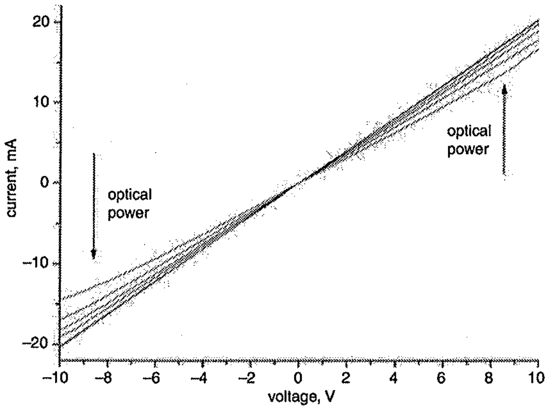

Fig. 4 *I(V) characteristic under illumination with an optical power between 0 and 300 mW*

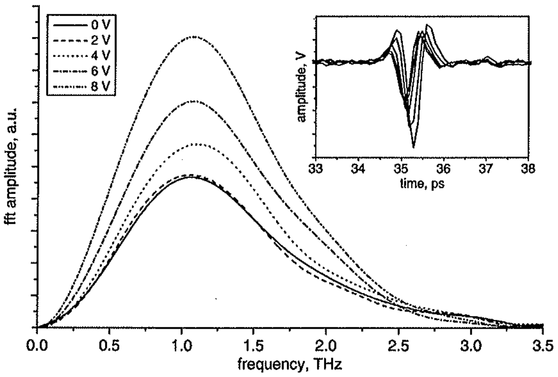

Fig. 5 *THz spectra at different bias voltages calculated from the time-domain response (inset)*

Conclusion: A new concept for the nano-fabrication of photoconductive interdigitated, large area THz emitters has been demonstrated. The few critical processing steps–interference lithography and metal evaporation under different angles–enable the combination of submicron and large-scale technologies in one device. Further improvement of the design to enhance the in-coupling of the excitation power, the conversion efficiency and the out-coupling of THz radiation are feasible by further optimisation.

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K. Huska, J. Hetterich, U. Geyer and U. Lemmer (*Lichttechnisches Institut, Universität Karlsruhe (TH), Karlsruhe 76128, Germany*)

E-mail: klaus.huska@lti.uni-karlsruhe.de

G. Klatt and T. Dekorsy (*Physics Department and Centre for Applied Photonics, University of Konstanz, Konstanz 78457, Germany*)

G. Bastian (*Faculty of Engineering, Fachhochschule Trier, University of Applied Sciences, Postfach 1826, Trier 54208, Germany*)

References

1 Mittelman, D.: 'Sensing with Terahertz radiation' (Springer Series in Optical Sciences, 2003)
2 Siegel, P.H.: 'Terahertz technology in biology and medicine', *IEEE T-MTT*, 2004, **52**, (10), pp. 2438–2447
3 Fitzgerald, A.J., Berry, E., and Zinov'ev, N.N., *et al.*: 'Catalogue of human tissue optical properties at terahertz frequencies', *J. Bio. Phys.*, 2003, **29**, (2–3), pp. 123–128
4 Dreyhaupt, A., Winnerl, S., and Dekorsy, T., *et al.*: 'High-intensity terahertz radiation from a microstructured large-area photoconductor', *App. Phys. Lett.*, 2005, **86**, (12), p. 121114
5 Dreyhaupt, A., Winnerl, S., and Helm, M., *et al.*: 'Optimum excitation conditions for the generation of high-electric-field terahertz radiation from an oscillator-driven photoconductive device', *Opt. Lett.*, 2006, **31**, (10), pp. 1546–1548
6 Awad, M., Nagel, M., and Kurz, H., *et al.*: 'Characterization of low temperature GaAs antenna array terahertz emitters', *App. Phys. Lett.*, 2007, **91**, (18), p. 181124
7 Acuna, G.P., Buersgens, F.F., and Lang, C., *et al.*: 'Interdigitated terahertz emitters', *Electron. Lett.*, 2008, **44**, (3), pp. 229–230
8 Bartels, A., Thoma, A., and Janke, C., *et al.*: 'High-resolution THz spectrometer with kHz scan rates', *Opt. Express*, 2006, **14**, (1), pp. 430–437
9 Bartels, A., Cerna, R., and Kistner, C., *et al.*: 'Ultrafast time-domain spectroscopy based on high-speed asynchronous optical sampling', *Rev. Sci. Inst.*, 2007, **78**, (3), p. 035107
10 Leitenstorfer, A., Hunsche, S., and Shah, J., *et al.*: 'Femtosecond high-field transport in compound semiconductors', *Phys. Rev. B*, 2000, **61**, (24), p. 16642