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# Optically excited THz generation from ordered arrays of GaAs nanowires

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**Abstract**

THz generation under excitation by ultrashort optical pulses from ordered arrays of GaAs nanowires is reported. It was found that the efficiency of THz generation is determined by the geometrical parameters of nanostructures and has a resonant character. Furthermore, it is shown that the terahertz generation efficiency at optimum geometrical parameters of an array of semiconductor nanowires is greater than the corresponding value for bulk semiconductor p-InAs which is the most effective THz emitter.



*Keywords:* Terahertz generation; THz; III-V semiconductors; NWs; nanowires; GaAs; light absorption; leaky mods; MOVPE

## 1. Introduction

The semiconductor nanostructures, such as free standing semiconductor nanowires (NWs), are one of the most promising low-dimensional nano-objects for applications in nanoelectronics, nanophotonics and nanobioelectronics. In addition, the use of such quasi-1D nanostructures, because of their unique electrical and

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optical properties, is an interesting direction for improvements in existing THz emitters [1-6]. The studies [3,6] have shown that the efficiency of a THz emitter can be substantially improved if the surface-to-volume ratio of the structure is increased. However, the real increase in the efficiency of THz generation in such nanostructures (with a structured surface) compared with the THz generation efficiency by bulk InAs has not been demonstrated. In this report, we present the experimental results of efficient THz generation by ordered arrays of GaAs NWs under the excitation by femtosecond optical pulses. Also, we highlight key factors influencing on the THz generation efficiency.

## 2. Samples

The GaAs NW arrays were grown by selective-area epitaxy using a horizontal metal-organic vapour epitaxy (MOVPE) system on n- and p- type GaAs (111)B substrates. More details in [7].

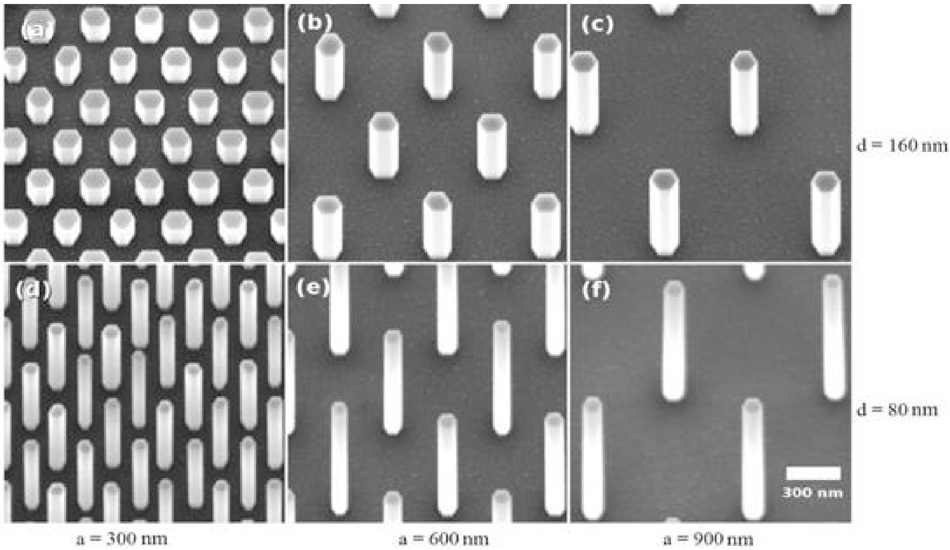


Fig. 1. 20° tilted scanning electron microscope (SEM) images of the fabricated GaAs NW arrays. The NWs are positioned where the openings were patterned. They have vertical sidewalls and exhibit a hexagonal morphology. Heights and diameters of the NWs depend on the opening size and array pitch (*a*). The 50 nm and 100 nm openings resulted in approximately 80 nm and 160 nm NW diameter (*d*), respectively, while the heights increased with increasing pitch. Average heights (*h*) for the NW arrays with 100 nm opening are listed in the inset of Fig. 3. The size of each array was 400x400 μm (inset of the Fig. 3).

## 3. Methods

The experiments were performed using time-resolved spectroscopy, which is able to detect the electric field amplitude and phase of THz radiation – a femtosecond pulsed laser is used to excite the NW arrays (orange line) and to probe the generated THz pulse (blue line). For the photoexcitation of structures we used Ti:Sapphire femtosecond laser, generating 15 fs light pulses at a repetition rate of 80 MHz with central wavelength about 800 nm. To obtain the excitation spectra of THz generation (Fig. 5) the laser with a tunable wavelength (from 710 nm to 910 nm), the duration of 40 fs and the repetition rate of 76 MHz respectively, was used, and the silicon bolometer was utilized for detection of generated THz radiation.

## 4. Results and discussions

The maximum amplitude of the THz pulse electric field was observed in the NW array with $a$ = 1200 nm (see Fig. 3), whereas the generation efficiency decreased when the distance between the NWs differed from this value. Moreover, for arrays with NWs shorter than 500 nm the sign inversion of the THz pulse electric field amplitude was observed. Similar behavior was observed for arrays with diameters of NWs $d$ ~ 80 nm, but in this instance the NWs were less than 600 nm long. It should be noted that the sign of the THz field generated from the bulk p-type GaAs substrate had the same polarity, but the amplitude of the field was much smaller. Despite the fact that the NW arrays

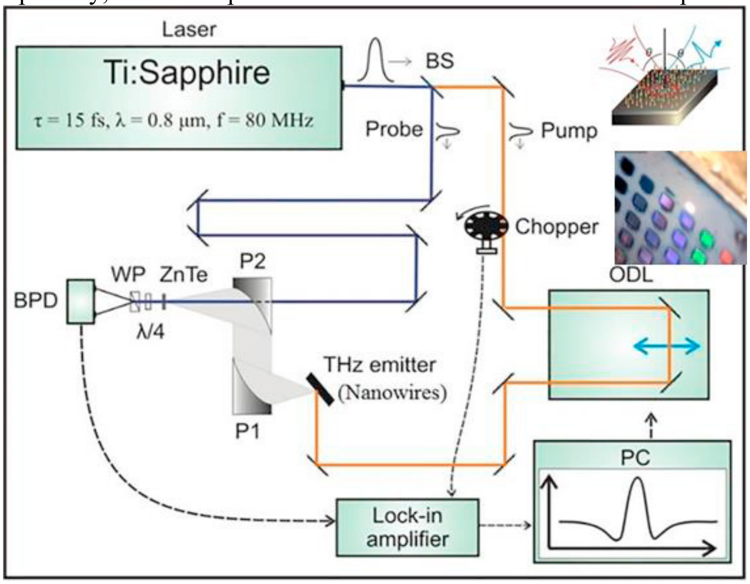


Fig. 2. Experimnetal Setup.

were grown on one and the same substrate, they still had different heights ($h$ on the inset at fig. 3) due to the peculiarities of the synthesis technique. For correct evaluation of the dependence of the THz field peak amplitude on the fill factor it is necessary to compare arrays with the same height of nanowires. (see Fig. 4). From the data obtained, it follows that the maximum efficiency of the THz radiation generation was observed when the NW pitch

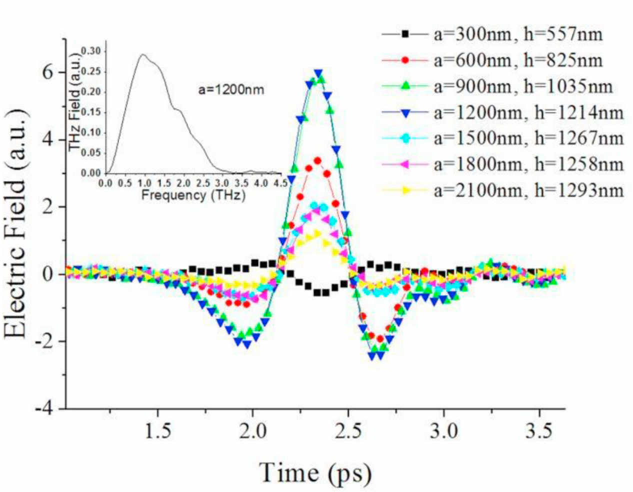


Fig. 3. Waveforms of the THz pulses for different NW arrays (on p-type GaAs (111)B substrates, $d$ = 160 nm).

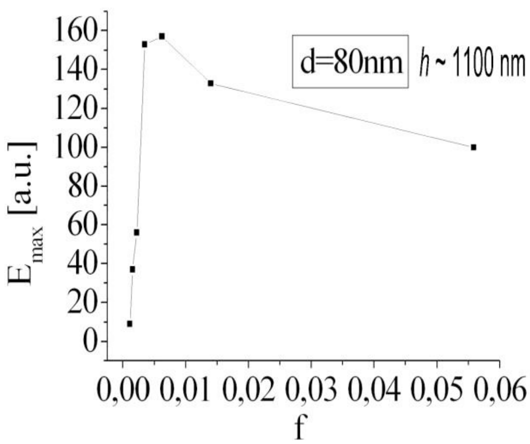


Fig. 4. Dependence of the maximum amplitude of on the NW the THz field on NW array fill factor.

*a* was of the order of the wavelength of the exciting light ($\lambda$ = 800 nm). When $a > \lambda$ (low fill factor), as shown in Fig. 5, there is a linear dependence. It indicates that in this case the efficiency of THz generation was proportional to the NW density. However, if $a < \lambda$ (high fill factor), THz field generated by an array of NWs decreases. Therefore, the assumption expressed by the authors of several publications about the significant growth of THz generation efficiency with an increase of the fill factor when $a < \lambda$ seems to be untenable.

Was also found that with certain NW parameters, the THz generation efficiency was highest with excitation polarization perpendicular to the NW axis and had a resonant character. These experimental results are well-described in terms of the mechanism associated with the leaky mode excitation at oblique incidence of light onto dielectric cylinder [8]. In [9], which was based on the theory of Lorenz-Mie, it was shown that when an electromagnetic plane wave falls onto an infinitely long dielectric cylinder, the resonant excitation of leaky modes occurs. In the case of an absorbing medium, the light absorption will occur in resonance as well. Therefore, the field amplitude inside the cylinder can exceed the value of the incident field by orders of magnitude under certain conditions. In view of the fact, that the magnitude of the THz field generated by the movement of non-equilibrium charge carriers in the near-surface or in the applied electric field, is proportional to the concentration of photoexcited charge carriers – the magnitude of the THz field will correlate with the amount of light absorbed. In Fig.5 the THz excitation spectra for bulk GaAs and GaAs NWs are presented. One can see that the excitation spectra for GaAs NWs has a resonance and its position coincides with the position of theoretically calculated absorption peaks for the single cylinder [7]. Thus, the experimental results shown in Fig. 5 can indeed be described in terms of the leaky mode excitation in NWs. In addition, the investigation of THz generation in the bulk p-InAs (p~$2\times10^{16}$cm$^{-3}$) showed that the efficiency of THz generation from ordered array of GaAs nanowires grown on the n-type GaAs (111)B substrate was higher than the THz generation efficiency from a bulk p-InAs (see Fig.6).

**Conclusion**

Thus, the experimental results indicate that the high efficiency of THz generation is determined by the amplification of the electromagnetic field due to the resonance excitation of the leaky modes (Mie resonances) in a nanocrystal. The maximum of THz field amplitude is achieved when the distance between the NWs is of the order of the exciting light wavelength with the corresponding values of NW's diameter. It was demonstrated that the efficiency of THz generation from ordered array of GaAs nanowires with the optimal geometry was higher than the THz generation efficiency from a bulk p-InAs semiconductor, which is today the most efficient coherent terahertz emitter.

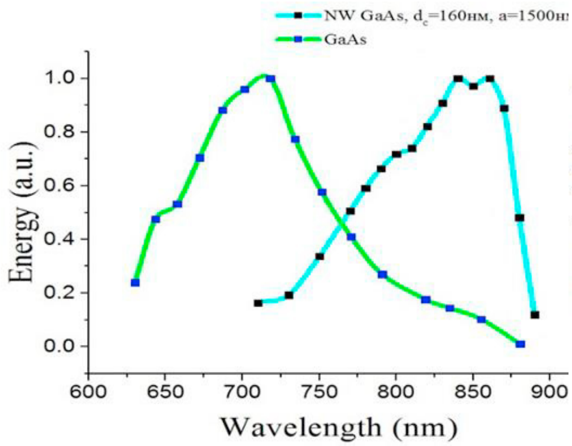


Fig. 5. THz excitation spectra. The dependence for bulk GaAs was taken from [10].

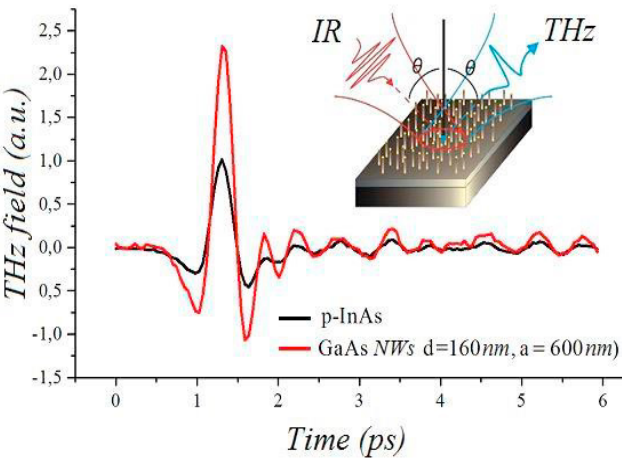


Fig. 6. THz generation efficiency from the ordered arrays of NWs (at an in an incident angle of 45°. n-type GaAs (111)B substrates) in comparison with bulk p-InAS. $\lambda$ = 800 nm.

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