Terahertz generation in 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 process is determined by the excitation of leaky modes for the light incident on the semiconductor nanocrystal and increases due to the resonant excitation of Mie modes. Furthermore, it is shown that the efficiency of the terahertz generation 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; Mie-absorption; leaky mods

1. Introduction

The semiconductor nanostructures, such as free standing semiconductor nanowires (NWs), are one of the most promising lowdimensional nano-objects for applications in nanoelectronics, nanophotonics and nanobioelectronics. In addition, the use of such quasi-1D nanostructures, because of their unique electrical and optical properties, is an interesting direction for improvements in existing THz emitters. Recent studies have shown that the efficiency of a THz emitter can be substantially improved if the surface-to-volume ratio of the structure is increased[1-2]. However, the real increase in the efficiency of THz generation in such structures, with structured surface, compared with the THz generation 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.

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.

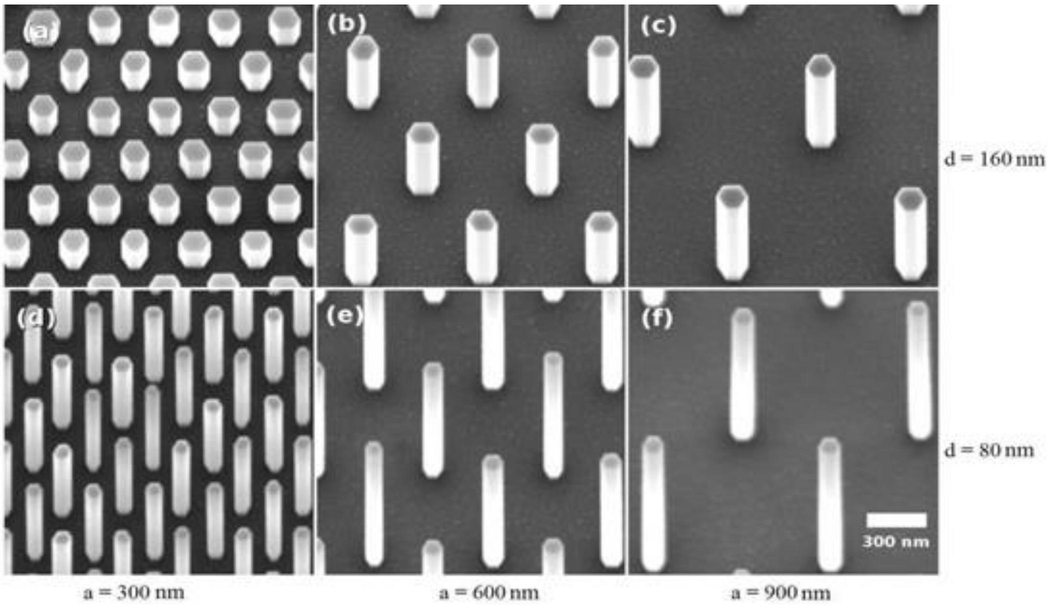

Fig. 1. 20° tilted scanning electron microscope (SEM) images of the fabricated GaAs NW arrays. The NWs are positioned where the openings were patterned. They have vertical sidewalls and exhibit a hexagonal morphology. Heights and diameters of the NWs depend on the opening size and array pitch (*a*). 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 200x200 μm (inset of the Fig. 2).

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 on central wavelength about 800 nm and the laser with a tunable central wavelength (from 710 nm to 910 nm), 40 fs and 76 MHz respectively, to obtaining the excitation spectra (Fig. 4).

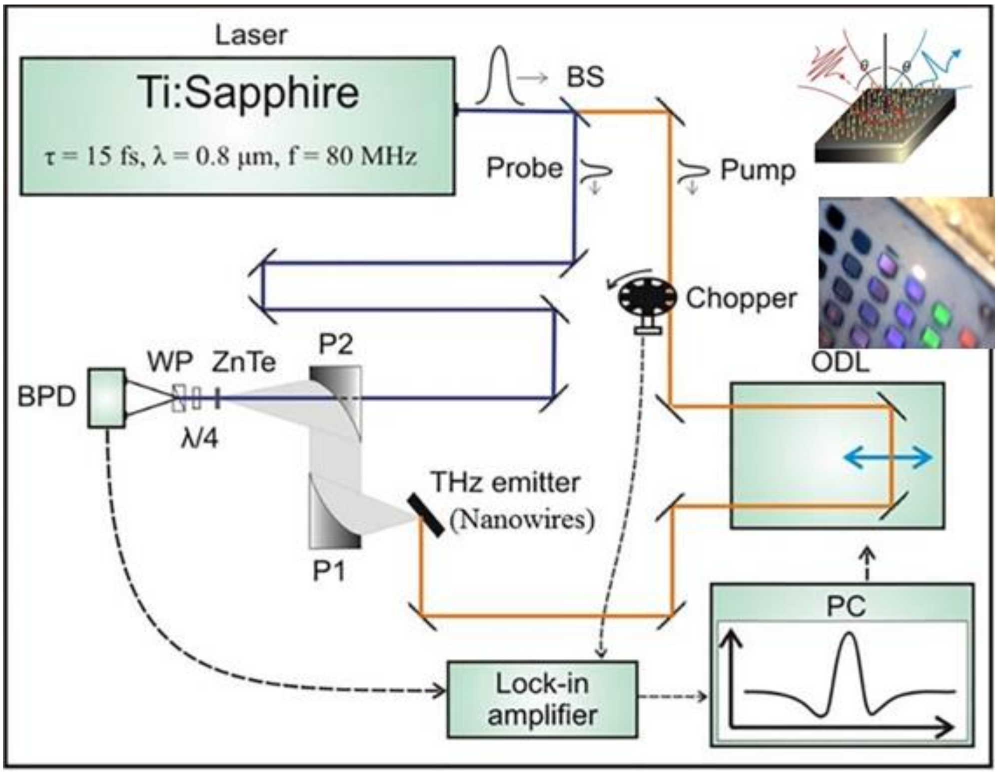

Fig. 2. Experimnetal Setup.

4. Results and Discussion

The maximum amplitude of the THz pulse electric field was observed to correspond to the NW array with a = 1200 nm (see Fig. 3), whereas the generation efficiency decreased as the distance between the NWs differed from this value. Further, there was a sign inversion of the THz pulse field amplitude for NWs shorter than 500 nm. Similar behaviour was observed for arrays with diameters of NWs d ~ 80 nm, but in this case 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.

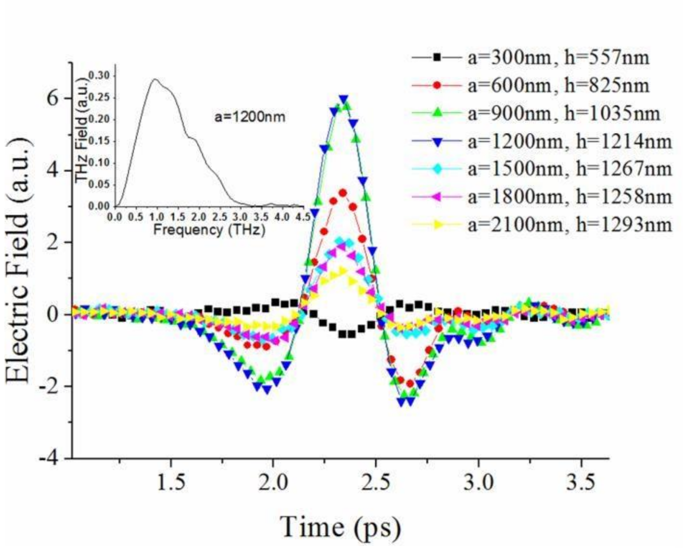

Fig. 3. Waveforms of the THz pulses for different NW arrays (on p-ype GaAs (111)B substrates, *d = 1*60 nm).

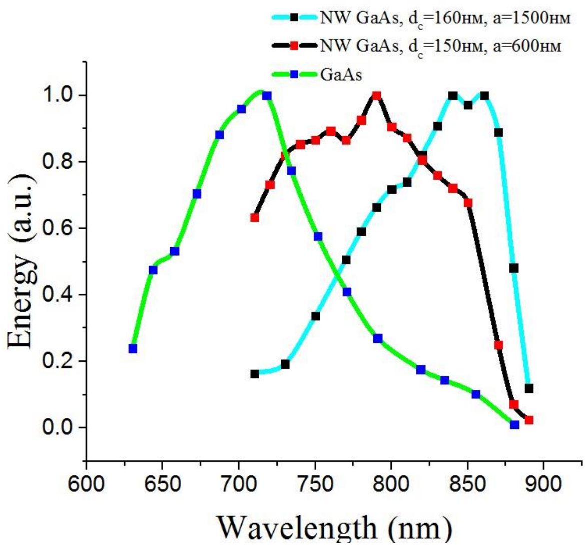

Fig. 4. The excitation spectra of THz generation.

To determine the nature of THz generation from NW arrays, first of all, it is necessary to investigate the dependence of the THz field peak amplitude on the array fill factor with equally long NWs (see Fig. 5). From the data obtained, it follows that the maximum efficiency of the THz radiation generation was observed when the NW pitch a was in the order of the wavelength of the exciting light ($\lambda = 800$ nm). When $a > \lambda$ (low fill factor), as shown in Fig. 6, 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 [1-3] about the significant growth of THz generation efficiency with an increase of the fill factor when $a < \lambda$ seems to be untenable.

In this case, the behavior of the THz field peak amplitude on the NW array filling factor (see Fig. 5) seems to be explained by the results obtained from the investigation of the dependence of the THz generation on the exciting radiation polarization. It was found that with certain NW parameters, the THz generation efficiency was highest with excitation polarization perpendicular to the NW axis.

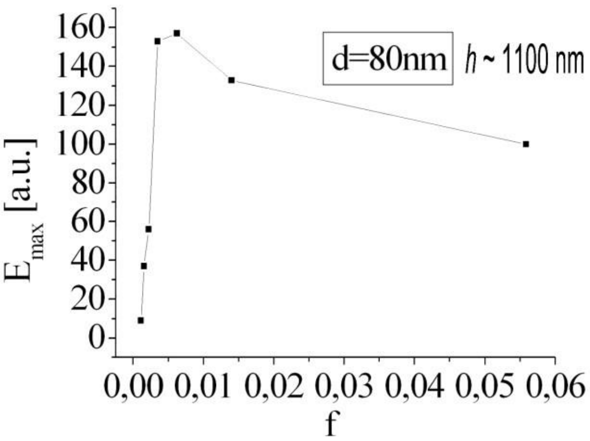

Fig. 5. Dependence of the maximum amplitude of on the NW the THz field on NW array fill factor.

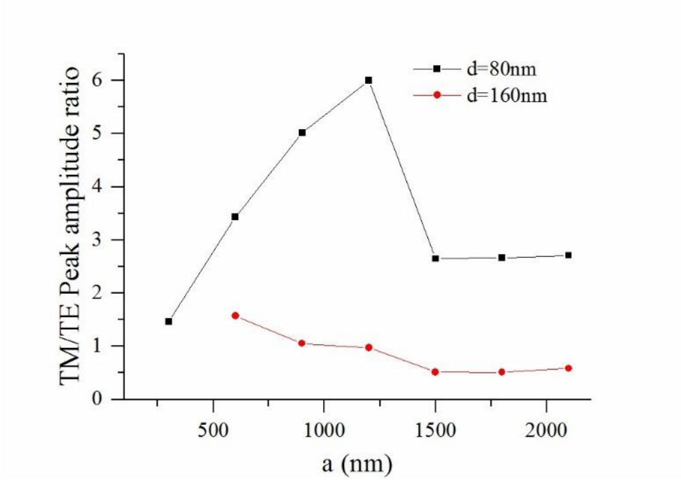

Fig. 6. Dependence of the ratio between the maximum amplitude of THz pulse for TM\TE polarization.

Fig. 6 shows the ratio between the maximum amplitude of the THz pulse for TM- and TE-polarization of the exciting radiation as a function of the NW array pitch. The angle of exciting light incidence was equal to 45°. According to the obtained data, if $a > \lambda$, the maximum THz field amplitude from an array of NWs with diameters d = 160 nm is approximately two times larger for the TE polarization than for the TM polarization. In contrast, in an array of NWs with diameter d = 80 nm, the peak amplitude of the TM polarization is two times larger than that of the TE polarization. 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. In [4], which were 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

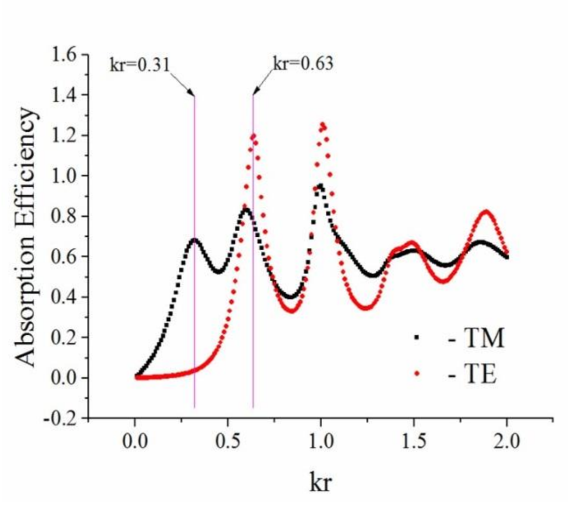

Fig. 7. Spectra of the absorption efficiency for TM- and TE- polarizations.

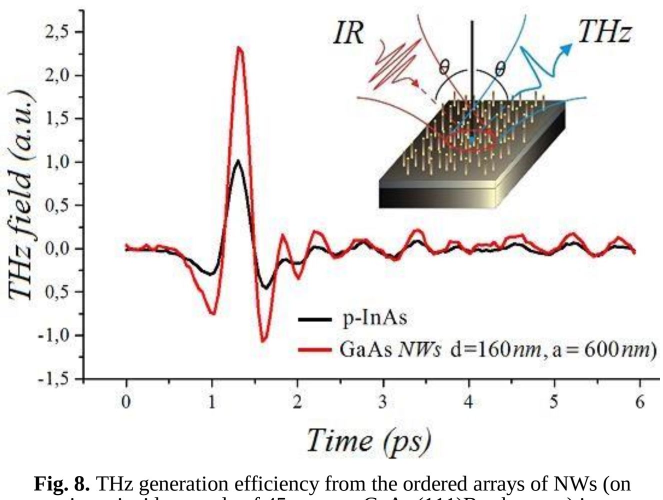

Fig. 8. THz generation efficiency from the ordered arrays of NWs (on in an incident angle of 45◦. n-type GaAs (111)B substrates) in comparison with bulk p-InAS. *Λ=795 nm.*

of magnitude under certain conditions. For ordered arrays of NWs with a diameter of 150 nm, the excitation spectra has a resonant character, thereby confirming the nature of the Mie resonance-enhanced terahertz generation (Fig. 4). Using data for the complex refractive index of GaAs, we can calculate the cross-section for the light absorption (Fig. 7) at oblique incidence on the characteristic value kr, where k is the wave vector of the excited light and r is the NW's radius. The light absorption was approximately two times greater for the TE- polarization as compared to the TM- polarization at a value of kr = 0.63 (d = 160 nm). The opposite behaviour was observed when kr = 0.31 (d = 80 nm). 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 [6]. Accordingly, the magnitude of the THz field will correlate with the amount of light absorbed. Thus, the experimental results shown in Fig. 6 can indeed be described in terms of the leaky mode excitation in NWs.

5. Conclusion

Thus, the experimental results indicate that the efficiency of THz generation process is determined by the excitation of leaky modes for the light incident on the semiconductor nanocrystal and increases due to the resonant excitation Mie modes. The maximum 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 the NW's diameter. It was demonstrated (Fig. 8) that the efficiency of THz generation from rdered arrays of GaAs nanowires grown on the n-type substrate was higher than the efficiency of THz generation from bulk p-InAs.

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