# THz Emission from InP and InGaAs Nanowires Fabricated Using Electron Beam Lithography

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*Abstract*— **THz emission from semiconductor nanowires has been an emerging trend since nanowires exhibit an increase in optical absorption by having a much larger effective surface area than films. The efficient THz emission is related to strong local field enhancement by coherent surface plasmons. In this work, we investigated THz generation from nanowires fabricated through a process that utilizes e-beam lithography and plasma etching, giving us full control of structural geometry such as the diameter, length, excellent-vertical alignment, and perfectly-uniform distribution.**

## I. INTRODUCTION

PICOSECOND optoelectronic switching, which was later named as photoconductive antenna (PCA), has been the most conventional method for THz generation since it was first introduced in the 1970s [1]. LT-GaAs has been most popular due to its controllable lifetime by the substrate temperature in epitaxial growth by molecular beam epitaxy (MBE), which actually requires a high voltage bias. It will be much simpler if we do not need high voltage bias. Recently, researchers have been looking for a good candidate for unbiased THz emission to replace conventional PCAs. It is well known that THz waves can be generated from semiconductor surfaces under the illumination of femtosecond optical pulses, which excite the surface at an oblique angle [2]. As the dimension of the material changes from wafer to an array of nanowires (NWs), under the same ultrafast laser spot size, the total effective surface area drastically increases resulting in a higher absorption that will play an essential role for enhanced THz emission intensity. There have been reports investigating the THz emission from a variety of semiconductor NWs, and one of these enlightening studies has been done on Ge NWs showing that THz pulse intensity emitted from Ge NWs is significantly higher than that emitted from a Ge wafer [3]. All the NWs samples that have been studied for THz emission were prepared by bottom-up growth processes, such as vapor phase epitaxy, chemical vapor deposition, etc. Bottom up processing is not the best method to prepare the NWs due to the lack of control on structural geometry of the wires, i.e., aspect ratio, vertical alignment, and uniform distribution. In this work, we suggest a top-down processing approach, fabricating the NWs with e-beam lithography and etching by which we can achieve excellent vertical alignment and perfectly uniform distribution of the NWs' with desired diameter and length.

## II. RESULTS

The samples discussed here are fabricated at the state-of the-art cleanroom user facility in the Center for Nanoscale Materials at Argonne National Laboratory. High quality lattice matched 1.2μm thickness of InGaAs epilayer was grown on InP substrate by Molecular Beam Epitaxy. The fabrication process began with bare wafers (InP and InGaAs for this study). A thin $SiO_2$ adhesion layer was deposited on the wafers by PECVD followed by spin coating of a negative resist HSQ (hydrogen silsesquioxane). E-beam lithography was used to write the mask for the NW patterns. Through a plasma etching process and removal of the resist by HF, we could achieve perfectly aligned NWs which were distributed exquisitely uniform along the wafer with a fixed pitch length on both x and y axes as shown in the Fig. 1(a) and 1(b), as an example of InP NWs.

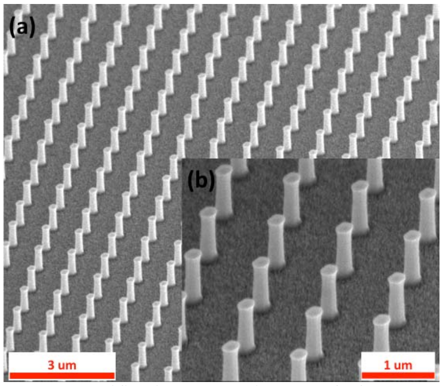

**Fig. 1.** (a) Low-magnification SEM image of the nanowire arrays, highlighting the perfect uniform distribution of the wires with a fixed pitch length. (b) Higher-magnification SEM image which shows the perfect vertical alignment.

Figure 2 describes the experimental set-up we used to generate THz radiation from the fabricated NWs. The experiment was conducted by using a mode-locked Ti:Sapphire ultrafast laser at a wavelength of 790 nm. This laser provides 120 *fs* pulses with a repetition rate of 76 MHz, which was split into two for emission and detection purposes. The laser pulse on the emission path is modulated through a chopper, whose frequency (2.4 kHz) is used as reference for detection, and then it is focused on the NW samples to generate THz pulses. The emitted THz pulses are collimated with a 90° off-axis parabolic mirror and focused on a PC antenna with another 90° off-axis parabolic mirror. In order to obtain a full spectrum, the ultrafast laser pulse split for detection path travels through a motorized delay stage, and it is focused on the PC antenna detector. In addition, a half-wave plate and a beam splitter pair was added on the pump beam path (emission path) so that we could run THz generation measurements with varying pump beam power to observe the dependency of radiated THz pulses on the excitation power.

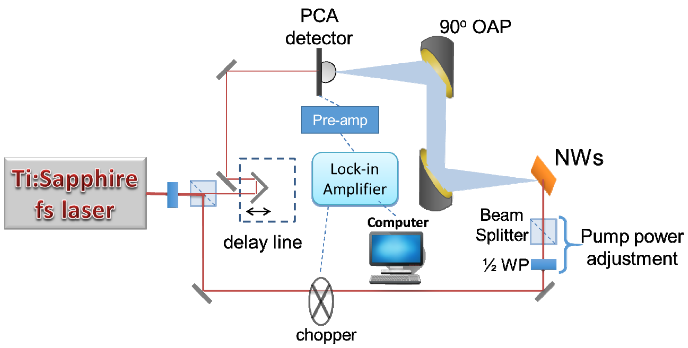

**Fig. 2.** Experimental set-up used for generation of THz pulses from the fabricated NW samples. A mode-locked 790nm Ti:Sapphire ultrafast laser with a pulse width of 120 *fs* was used for both pump and probe beams.

Figure 3 shows the measurement results of excitation power dependent THz emission spectra from InGaAs NWs sample with a diameter of ~100 nm. Strong THz pulse generation is observed from the fabricated InGaAs NWs without any bias voltage. It can be seen in Fig. 3(a) that the radiated THz field from the fabricated InGaAs NWs increases with the increasing pump power, but the increment gets smaller when we escalate the pump power. This result can be observed more clearly when we look at the peak-to-peak THz field amplitude with varying pumping power in Fig. 3(b), which states that THz emission saturates even though we keep increasing the excitation power. This saturated profile is attributed to penetration depth of 790 nm light into InGaAs, which is ~200 nm [4]. The absorption of the infra-red (IR) laser pulse by the InGaAs NWs with the diameter of 100 nm saturates while excitation power increases due to the penetration depth which results in a saturated profile of the emitted THz pulse from these NWs. From the THz emission spectrum, we observed the pulse width is about 1ps, which is relatively shorter than the THz emission pulses compared to 2ps from commercial InGaAs PCAs.

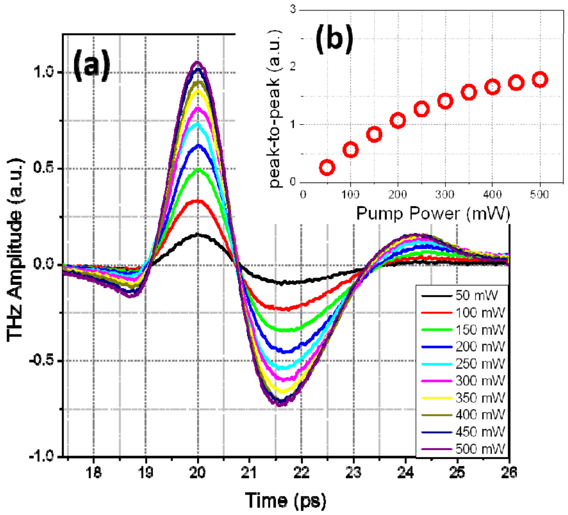

**Fig. 3.** (a) Emitted THz fields from the fabricated InGaAs NWs (dia. = 100 nm) surfaces with varying pump power. (b) Saturated profile of peak-to-peak amplitude of the THz emission with increasing pump power.

Peak-to-peak intensity of the THz generated from our nanowire samples can be seen in Fig. 4 (a) with respect to different pitch values for InP NWs. Nanowire densities are $1x10^8$ $cm^{-2}$, $4.4x10^7$ $cm^{-2}$, and $2.5x10^7$ $cm^{-2}$ for the pitch values of 1.0μm, 1.5μm, and 2.0μm, respectively. By increasing pitches, nanowire densities would decreases, which results in decreasing effective surface area where the pump beam is to be absorbed. Hence, THz emission gets weaker when pitch increases as it is observed in case of InP NWs samples in Fig. 4(a). THz wave radiation from InGaAs NWs sample was stronger than that of InP NWs samples even though nanowire density was lower. This result can be explained by the higher carrier concentration and greater electron mobility of InGaAs compared to InP.

We also measured THz emission from InGaAs NWs under the illumination of ultrafast laser pulse with two different linear polarizations: p- and s- polarized light as shown in Fig. 4(b). The arrows on the NWs indicate the direction of the coherent surface plasmon motion under each polarization. The measurement clearly exhibits that for the most efficient THz emission, the NW ensemble should be excited by p-polarized femtosecond laser pulse which would oscillate the charges along the wire resulting in a THz radiation in the direction of the surface normal of NWs.

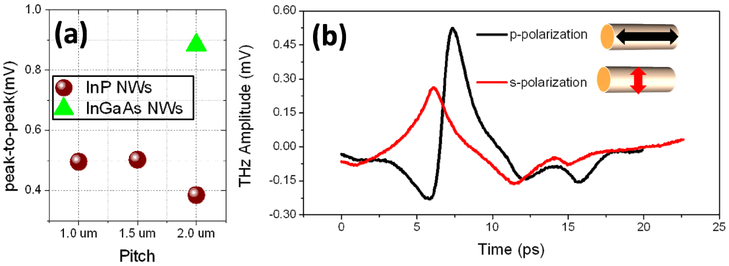

**Fig. 4.** (a) Peak to peak intensity of emitted THz radiation in comparison with three different pitch sizes for InP NWs and InGaAs NWs sample. (b) THz emission from fabricated NWs when excited by two different linearly polarized femtosecond laser pulse.

## III. SUMMARY

In summary, we investigated the methods to enhance the efficiency of THz emission from semiconductor NWs. We suggested fabricating the NWs by e-beam lithography and etching to provide full control of geometry, vertical alignment and uniform distribution of the NWs, which plays an essential function in THz emission. We also examined the roles of the laser pulse polarization and the excitation power on the emitted THz intensity.

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