行政院國家科學委員會補助專題研究計畫 ■成果報告 □期中進度報告

（計畫名稱）

近場兆赫頻波光譜研究

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執行機構及系所：

計畫主持人：安惠榮
共同主持人：
計畫參與人員：

成果報告類型(依經費核定清單規定繳交)：□精簡報告 ■完整報告

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中　華　民　國　年　月　日

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■ 達成目標

✧ 未達成目標（請說明，以 100 字為限）

✧ 實驗失敗

✧ 因故實驗中斷

✧ 其他原因

說明：

2. 研究成果在學術期刊發表或申請專利等情形：

論文：■已發表 □未發表之文稿 □撰寫中 □無

專利：□已獲得 □申請中 □無

技轉：□已技轉 □洽談中 □無

其他：（以 100 字為限）

Through this project 9 SCI papers were published in high-IF journals including Nano Letters, Applied Physical Letters, Optics Express, and Applied Physics Express and 3 conference proceedings. 6 international conference papers have been presented in world-leading conferences in optoelectronic fields, such as CLEO, SPIE/OPTO, and Material Research Society meeting and two papers will be presented in Frontiers of Optics and 2013 SPIE/OPTO next January. 9 domestic conferences papers were presented in OPT and Chinese Physics Society meeting. In particular, I was invited to SPIE Photonic West 2011 and MRS 2009 Fall meeting.

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以500字為限）

Under the support of National Science Council, we have established a high-resolution terahertz imaging system, consisted of an inverted optical microscope and AFM manipulating system. With this system terahertz spectroscopy of highly absorbing and ultrathin materials can be investigated in the frequency of 0.3 – 2.2 THz. The signal-to-noise ratio of terahertz pulses is typically of the order of 10^6. Metal tip manipulation and sample rastering systems are installed and tested. The performance and the repeatability of the new terahertz spectroscopy system were checked by measuring the electrical properties of well-known materials including the InN film and Si wafer. Comparison of results with those measured by transmission-based terahertz spectroscopy system shows an excellent agreement. In order to demonstrate the prospect of newly established THz-reflection-TDS, we investigated the electrical properties of silver nanowires. Thin oxide layer would hinder the electron transportation through the junction, but the influence of oxidation to the device performance has not been systematically studied and the results reported to date were obtained by the destructive method such as TEM imaging. By using THz-RTDS, we succeeded in measurement of electrical conductivity of Ag nanowires and the influence of natural oxidation on conductivity of Ag nanowires could be clarified. Since Ag nanowire layer is highly absorbing in terahertz range, it was extremely difficult to perform THz-transmission-TDS. And this demonstrates the feasibility of THz-RTDS on absorbing and also very thin materials.

We also performed ultrafast carrier dynamics study and time-domain THz spectroscopic study on semiconductors. A comprehensive investigation of carrier dynamics in the InN nanorod arrays was achieved by measuring the probe wavelength and polarization dependence of transient reflectivity. We observed abnormally short carrier relaxation time which is due to the fast trap of carriers by surface-associated defects in the very narrow nanorods. In the carrier dynamics study of Mg-doped InN, the decay time constant of InN:Mg depends on background electron density in the same way as terahertz radiation does.

From the measurement of THz emission from Mg-doped c- and a-plane InN, we found that THz emission from Mg-doped InN is critically dependent on background carrier density. For Mg-doped c-plane InN, a transition of dominant terahertz emission mechanism between the photo-Dember effect and surface field acceleration occurs depending on the carrier concentration. THz waves from *a*-InN:Mg and the polarity of these waves are background carrier-insensitive, which can be attributed to carrier transport in a polarization-induced in-plane electric field. Optical emission mechanisms of semiconductor nanostructures have been studied by measuring time-integral and time-resolved photoluminescence. We first measured the strong green PL from InGaN/GaN nanorods and found that the enhancement of the green light emission from epitaxially-grown InGaN nanorods is due to the radiative recombination of deeply localized excitions associated with the increased composition non-uniformity in the nanorods. The enhancement of light emission from the same InGaN nanorods was achieved by coupled to a gold plate through a SiO2 dielectric nanogap layer. And finally, the 3D sub-diffraction-limited laser operation in the green spectral region based on a metal_oxide_semiconductor (MOS) structure could be realized.

目錄

一、 中、英文摘要

The capability of characterization of electrical properties of materials by using optical method has made THz spectroscopy one of the most attractive topics in optics and material science fields. For last few years, we have established the comprehensive optical and terahertz (THz) characterization system for semiconductors and their nanostructures. In the THz field, our research includes the search for the THz emission and enhancement methods and THz spectroscopic study on the material property diagnosis. Due to its small photon energy, THz wave can detect the dynamics of free electrons and time-domain detection of THz field makes it possible to measure the electrical properties as well as optical properties of materials. In a recent THz spectroscopic study on InN nanorod arrays, we have demonstrated that the electrical conductivity of nanostructures can be deduced from THz spectroscopy, which cannot be obtained by conventional direct, contact methods such as Hall effect measurement. With the recent rapid development of THz sources, the uniqueness of THz radiation in material and device characterization has stimulated the rapid development of THz imaging techniques. Due to its long wavelength, however, THz waves cannot be equally applied to map the dielectric responses of most of semiconductor devices or nanostructures. In addition, most of THz spectroscopy is based on transmitted THz signals through the sample so that it has several intrinsic limitations in investigation of very thin or very absorbing materials. Recently, the concept of near-field scanning microscopy was applied to obtain spatial resolution below the diffraction limit at various wavelengths, including THz regime. Coupling of near-field microscopy with THz spectroscopy enables a noncontact optical measurement of the electric conductivity of nanostructured semiconductor and even metals. We have set up a reflection-based THz spectroscopy system with a PZT modulated metal tip. Through the comparison with the results of transmission-based THz spectroscopy, we tested the performance of the new system. Moreover, measurement of conductivity of silver nanowires reveals the merits of reflection-type THz spectroscopy compared to those of transmission-type THz spectroscopy. We have successfully investigated the optical and electrical properties of semiconductor films and nanostructures by conducting THz spectroscopy and ultrafast optical spectroscopy.

二、 關鍵詞 (keywords)

兆赫波產生, 氮化銦, 時間解析光頻和兆赫波時區光譜, 螢光頻譜

THz emission, InN, THz time-domain spectroscopy, photoluminescence

三、 報告內容

1. 前言

THz science and technology has become one of the most exciting research frontiers in recent years. This long-neglected portion of the electromagnetic spectrum has begun to attract a great attention, because of the many possible applications ranging from basic science to applied engineering. One of the key factors motivating the ongoing development of THz system is the potential for new sensing paradigms based on the use of THz radiation for spectroscopic identification of nanostructures. THz time-domain spectroscopy has become a popular method to obtain information on the far-infrared properties of molecules, semiconductors, and other materials, and has shown to be promising technique to image objects. Current trend in development of nanometer-scale devices requires techniques that can measure the high-frequency permittivity of semiconductor surfaces in nanometer scale. The knowledge on the dielectric function of materials is particularly important for devices aiming to operate at the high frequency (over GHz) since it can affect device performance. In recent years, THz spectroscopy has attracted great attention as a novel method to measure the dielectric functions of charge carriers in contactless way and the time-resolved THz spectroscopy with sub-ps temporal resolution has demonstrated many pioneering results of carrier dynamics.

For last few years, we have established the comprehensive optical and terahertz characterization system for semiconductors and their nanostructures.[1-12] In a recent THz spectroscopic study on InN nanorod arrays, we have demonstrated that the electrical conductivity of nanostructures can be deduced from THz spectroscopy, which cannot be obtained by conventional direct, contact methods such as Hall effect measurement.[11] Due to its long wavelength, however, THz waves cannot be equally applied to map the dielectric responses of most of semiconductor devices or nanostructures. Under the support of National Science council, we have set up a reflection-based THz spectroscopy system with a PZT modulated metal tip. During the installation and test process, we realized that transmission-based THz-TDS has several intrinsic limitations in investigation of very thin or very absorbing materials. For example, silver nanowires, which has excellent transparency in the visible spectral range, have high THz absorption and cannot be realized by transmission-based THz spectroscopy. Especially, the transient conductivity depending on the level of oxidation of Ag nanostructure could not be measured by the Hall effect measurement. Coupling of near-field microscopy with THz spectroscopy enables a noncontact optical measurement of the electric conductivity of nanostructured semiconductor and even metals. This measurement of conductivity of silver nanowires reveals the merits of reflection-type THz spectroscopy compared to those of transmission-type THz spectroscopy. We have also conducted the experiments to realize the optical and electrical properties of semiconductor films and nanostructures by using THz spectroscopy and ultrafast optical spectroscopy.

2. 研究目的

Characterization of material properties, especially electrical properties, is generally achieved by employing contact-mode measurement methods, such as the Hall effect measurement. However, the continuing miniaturization of semiconductor devices into the nanoscale regime has emphasized the importance of understanding the optical/electrical properties of individual nanostructures. Recently, THz spectroscopy emerges as an alternative and yet a unique method to investigate the electrical properties of nanostructures. In recent years, the advances of ultrafast laser technology and their applications to material science are immense. By replacing ultrafast THz waves as the probe beam, near-field microscopy technique can be applied to investigate the spectroscopic characterization of nanostructured materials on a sub-wavelength scale. THz time-domain spectroscopy not only provides the electrical conductivity and carrier density, but also gives the information of the electron-electron scattering time. Ultrafast electron scattering time corresponds to the average time between collisions and can reveal the carrier transportation between nanostructures, which is an important issue for further development of nano-devices. The project is first aimed to develop a method to create and detect a local THz source with a sub-wavelength resolution, which has the potential to image microscopic objects. This can open the door to quantitative studies of local carrier concentration and mobility at the nanometer scale with a contactless probe. The dependence of carrier transportation on the growth and structural conditions then can be investigated for the samples with different growth axis, dopants, and structures. Meanwhile, THz spectroscopy is typically practiced by measuring the transmitted THz signals through the samples. But it has an intrinsic limitation on the thin film or very absorbing material. Recently, metal nanostructures, such as silver nanowires, attract a great attention as promising electrodes due to their ability to provide high transmittances. Despite of the potential prospects, the systematic study on the thickness of the nanowire films and the oxidation has not been reported. With the newly established reflection-based THz spectroscopy system, the electrical properties of those metal nanostructures can be systematically studied.

3. 研究方法

The schematic and the basic experimental setup of reflection-based THz spectroscopy system are shown in Fig. 1 and 2, respectively. Ultrafast THz wave is generated from a multi-strip photoconductive antenna photoexcited by a Ti:sapphire laser with the repetition rate of 80 MHz at the center wavelength of 800 nm. THz wave is delivered and focused on the sample surface by a parabolic mirror at the typical incident angle of 60°. Reflected or scattered THz wave is detected by an intensity detector, Golay cell or the

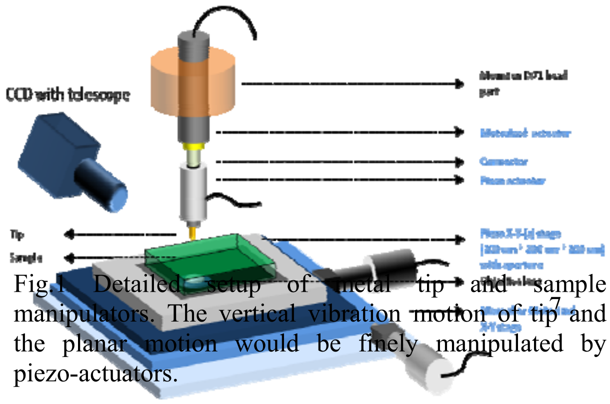

Fig.1 Detailed setup of metal tip and sample manipulators. The vertical vibration motion of tip and the planar motion would be finely manipulated by piezo-actuators.

time-domain EO sampling method with a 1 mm-thick ZnTe crystal, in which the Pockels effect due to the THz field rotates the polarization of the sampling laser pulses. A balanced detector detects the differential photocurrent as a function of time delay between the THz pulses and optical probe beam. Golay cell is highly sensitive THz intensity detector, but is much easier to handle than a bolometer. All the measurements were done under dry nitrogen purge. Vibrating motion of metal tips and the scanning function would be provided by the motorized manipulators and they were mounted on the inverted optical microscope (Olympus IX71). Instead of rastering metal tips to scan the image, the sample is located on the top of 3D manipulator and the vibrating motion would be provided by a piezo-actuator.

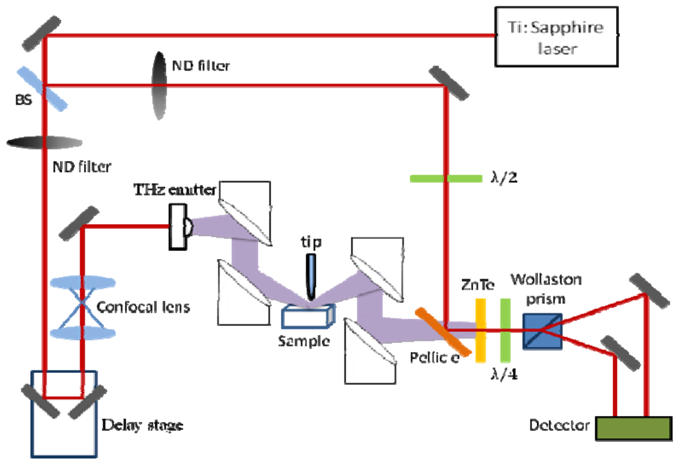

Fig. 2. The experimental set-up for the THz time-domain spectroscopy. The major part of laser pulses are delivered to a pc-antenna for THz emission and weak laser pulses are used as the probe beam with time delay. Two parabolic mirrors are used for collection and collimation of the generated THz pulse and the samples were placed in the way of collimated THz beam. The terahertz pulses were detected by free-space electro-optic sampling in a 2-mm-thick ZnTe crystal as a function of delay time with respect to the optical pump pulse.

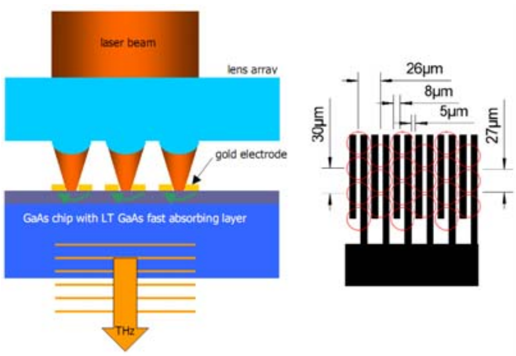

Fig. 3 iPCA from Batop which is consisted of lens array and multi-strip antenna on top of LT-GaAs substrate

The multi-strip antenna (iPCA) we used is from Batop Corp. and as one can see in Fig. 3, laser beam can be focused on the individual strip dipole by a lens array. It has the advantages of easy coupling of light into individual dipole detector and stronger THz emission than a single dipole antenna. Figure 5 shows THz emission power as a function of applied electric field strength calculated by $P_{THz} = \frac{C \cdot E \cdot E_{sat}}{A}\left[1-e^{-E/E_{sat}}\right]P_{sat}^{2}\left[1-e^{-P_{opt}/P_{sat}}\right]^{2}$, where C=1.51x10^{-23} m^{4}A^{-1}V^3 (specific coefficient), A=3.3 x10^{-7} m^2 (illuminated area of the PCA), E=V/g (electrical field strength within the gap), E_{sat}=1.5 MV/m (saturation electric field strength), P_{opt} is mean optical power, Ps_{at}=0.97 W (saturation optical power), V is gap voltage, and g=5 μm (gap distance). The typical waveform and the Fourier transformed spectrum of iPCA are shown in Fig. 6. The signal-to-noise ratio of iPCA can reach ~10^7 when it is photoexcited by femtosecond laser pulses with ~480 mW of power and the available spectral range measured by EOS detector based on 1-mm thick ZnTe is <2.5 THz.

To achieve the spectroscopic study of nanostructures, it is necessary to build a time-domain detection system. Without metal tip manipulation to extract the near-field, our imaging setup is a time-domain THz reflection measurement system. Since time-domain THz detection system can measure the THz field amplitude and the phase simultaneously, frequency dependent dielectric constants and the conductivity of the materials can be obtained directly. Prior to perform THz time-domain reflection measurement, we have measured the electrical properties of semiconductors in THz transmission measurement system which would be combined with the result of reflection measurement and provide the THz absorption information of materials.

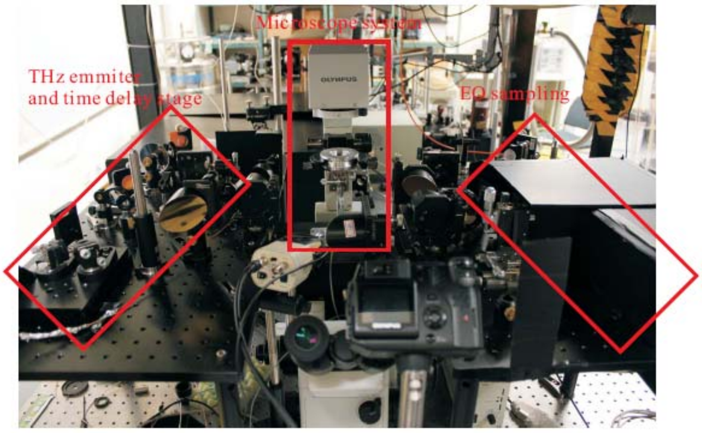

Fig. 4. A photo of experimental setup of the THz near-field imaging system. Vibrating motion of metal tips and the scanning function are provided by the motorized motion manipulators and they are to be mounted on the inverted optical microscope.

- **Samples in use**

Silver nanowire (AgNW) films were prepared by spin-coating method on Si substrates. The transparency and surface coverage were determined by adjusting the spinning speed or the AgNW solution density. The image in Fig. 3 shows a scanning electron microscopy (SEM) image of AgNWs on Si. Typical tube lengths were a few tens of micrometers and typical diameters were ~100 nanometers. The AgNW morphology is characterized by void regions where the substrate is fully exposed and narrow ridges corresponding to the nanowires.

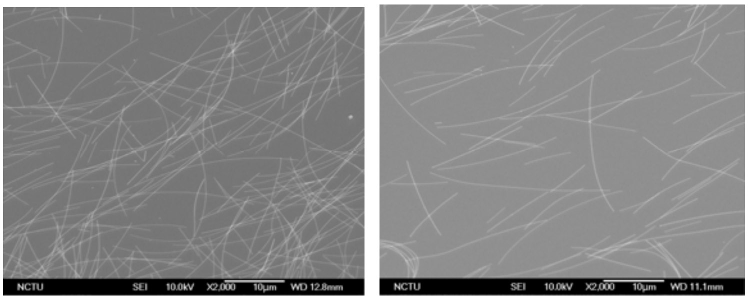

Fig. 5. A scanning electron microscopy (SEM) image of AgNWs on Si with the solution density of (a) 1/36 and (b)1/72. Typical tube lengths were a few tens of micrometers and diameters were ~100 nanometers. The number of junction that NWs are overlapping is much smaller for NW film with the density of 1/72.

Thin gold film was deposited on a glass substrate to be use as a reference material for reflection-based THz spectroscopy. The calibration of the metal tip position was also done with this gold thin film. For THz spectroscopic research and carrier dynamics study, several *a*-InN and Mg-doped *a*-InN films were grown on *r*-plane $\{1\bar{1}02\}$ sapphire substrates, whereas –*c*-plane $(000\bar{1})$ undoped and Mg-doped InN films with a thicknesses of ~ 1.2 μm were grown on Si(111) substrates by plasma-assisted molecular beam epitaxy. Both c-InN epilayer and Si substrate were used as a reference material to check the performance of newly established reflection-based THz-TDS system. Mg doping was performed with a high-purity Mg (6N) Knudsen cell and the Mg doping level was controlled by regulating the cell temperature between 180 and 290 ˚C. The electron density and mobility of the samples were separately determined by room-temperature electron Hall effect measurement for comparison with the results of THz-TDS. Vertically-aligned InN NR arrays were grown on Si(111) substrates. The InN nanorods were grown at a sample temperature of 520 ˚C on Si substrates and the rod density and diameter were controlled by means of the N/In ratio. For comparison of results, an InN epilayer was grown on Si(111) by using the epitaxial AlN/β-Si_3N_4 double-buffer layer technique. The epitaxial growth proceeded nominally under N-rich (N/In=6.0) conditions, which resulted in the desired columnar morphologies.

4. 結果與討論

We measured the reflected THz signal as the height over an extended Au surface decreases and Fig. 6 illustrates the THz waveform and spectrum measured at different tip height. The changes of waveform and spectrum near 0.5 THz are due to the near-field THz wave. Not only Au thin film, but also Au nanoparticles were prepared for the investigation of the signal enhancement by the surface plasmon. 2D assembly and 3D multilayer Au structures were tested in Z-scan measurement system separately developed to investigate the nonlinear optical properties. The high repetition rate of our laser system, however, causes the thermal excitation of highly conductive Au nanostructures so that the correct information of material properties could not be obtained. This problem can be

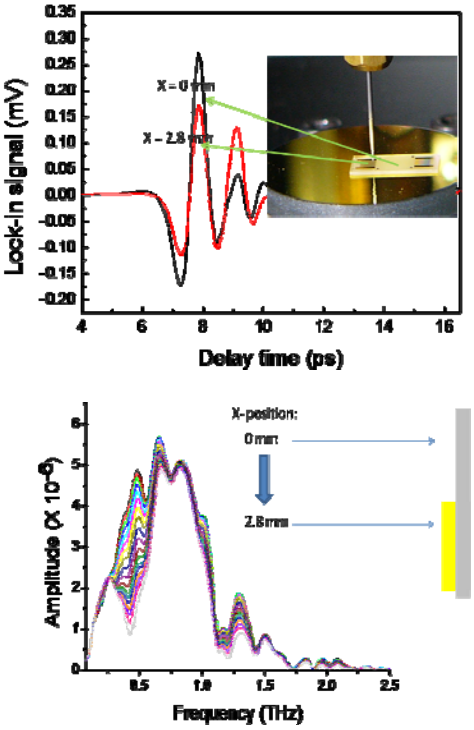

FIG. 6. Reflected THz waveforms and the THz spectrum as the distance between the Au film and the metal tip is adjusted

solved only by reducing the repetition rate of the laser system using, so-called, a pulse picker to at least a few tens of kHz, which we do not have currently. The performance of newly established THz reflection spectroscopy system was tested by measuring the previously identified materials. We took Si substrate and a c-plane InN film as the reference materials. Figure 7(a) shows the Drude-like electrical conductivity of the *c*-plane InN film and the real part of refractive index of ~3.41 is consistent with the well-known value of Si wafer These results are in the excellent agreement with those measured by the separately installed transmission-based THz-TDS system in our laboratory. Further measurements on other materials and the comparison with the results of transmission-based THz-TDS confirm the performance of our reflection-based THz-TDS system and we used this system to measure the electrical properties of Ag nanowires.

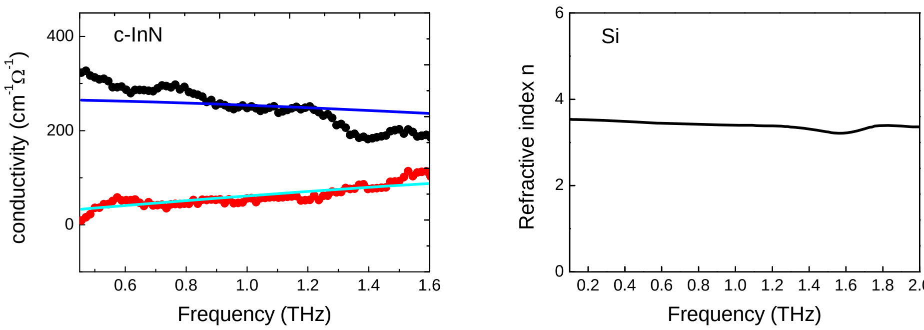

Fig. 7. (a) Frequency-dependent electrical conductivity of the c-plane InN film measured by THz reflection TDS system. The frequency dependence of conductivity could be described by the simple Drude model and the fitting parameters used in the simulation are consistent with those obtained by THz transmission TDS system. (b) The complex refractive index of Si substrate measured by THz reflection TDS system. The real part of refractive index of ~3.41 over the frequency range between 0.1 THz to 2.0 THz is consistent with that of THz transmission TDS.

We have also performed several researches on III-V nitrides using THz spectroscopy and ultrafast carrier dynamics. As an extension of the research on photoluminescence measurement of semiconductors, we studied the PL of InGaN/GaN nanorods on metal oxide and succeeded in building the smallest nanolaser based on surface plasmonics. The results of these research are summarize in the following.

✧ Oxidation of Ag nanowires studied by THz-reflection-TDS

Indium oxide (ITO) has been widely used as plastic substrates with high transparency and low sheet resistance for printed electronic devices. However, ITO is quite brittle so that there has been a demand on a new material to replace ITO. Conducting polymers, metal inks, nanoparticulate metal oxides, carbon nanotubes, and graphene have been investigated as potential alternatives, but none can yet compete in terms of transparency and sheet resistance. Thin meshes of silver nanowires have recently emerged as promising electrodes due to their ability to provide good transmittances (>85%) at sheet resistances less than 20 Ω sq^{-1}. Their application to printed electronics, however, is challenging due to a highly non-uniform topography (as it can be seen in Fig. 5), which can cause shorting through other layers. We used the THz reflection spectroscopy to measure the conductivity and oxidation problem of Ag NWs. Through the collaboration with Prof. P. Yu in Department of Photonics in National Chiao Tung University, we prepared the Ag NW film by spin coating method. Figure 8(a) shows the frequency-dependent electrical conductivity of Ag NWs with the NW density of 1/36 right after the NW film was prepared. Despite the individual NW has nanostructures, nanowires can be overlapped in the junction and form a wide mesh of silver. Therefore, the frequency-dependent electrical conductivity in Fig. 8(a) still shows the simple Drude-like behavior, indicating very conductive metal mesh. We measured THz spectroscopy of the same Ag NW film four weeks later and the frequency-dependent conductivity in Fig. 8(b) is nearly identical to the one in Fig. 8(a).

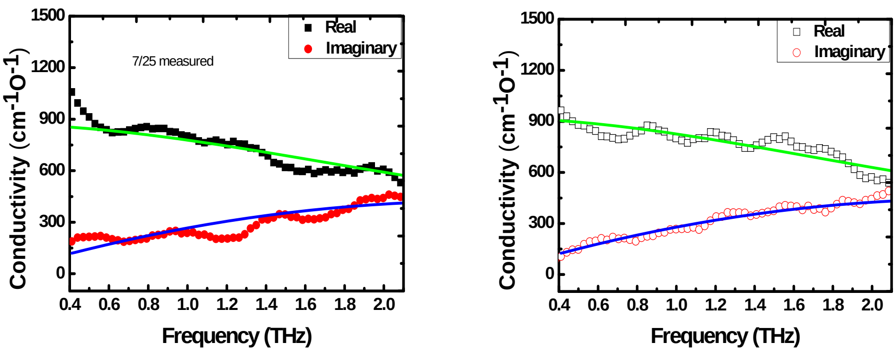

Fig. 8. Frequency-dependent electrical conductivity of AgNWs on Si with the NW density of 1/36 measured (a) right after the growth and (b) one month later. Both show the Drude-like metal behavior.

We performed the same measurement on the Ag NW film with the NW density of 1/72. The conductivity measured right after the film was prepared [Fig. 9(a)] shows the Drude-like behavior, but the one measured about four weeks later shows clearly non-Drude dependence on the frequency. This frequency-dependence can be described by, so-called, Drude-Smith model which is well-accepted to explain the frequency-dependent conductivity of nanostructures. We attribute this change of conductivity to oxidation of Ag NWs. Right after the growth of Ag NWs, the junctions between wires are electronically conductive and build a large conductor mesh over the whole film and behave like a two-dimensional conductive film. As the time passes, the surface of each NW oxidizes and forms thin Ag-oxide layer surrounding the NW. Then at the junction of NWs, electron transfer can be prevented by the thick-enough Ag-oxide and electrons would be confined in each NW. Then the whole film is like a stacked nanowires which are electrically independent.

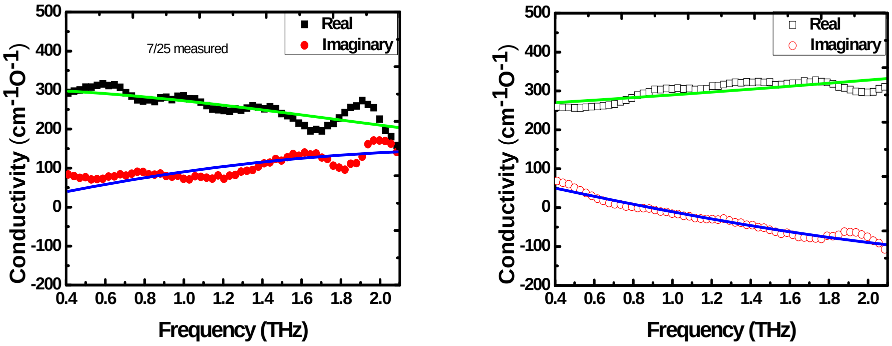

Fig. 9. Frequency-dependent electrical conductivity of AgNWs on Si with the NW density of 1/72 measured (a) right after the growth and (b) one month later. While conductivity signals in Fig. (a) can be explained by the Drude model, the one in Fig. (b) follows the Drude-Smith model which is due to the confined electrons in nanostrucutres.

We measured the same Ag NW samples in THz transmission spectroscopy system. But the absorption of THz waves in Ag NWs is very high so that we could not get the reasonable data. This proves the benefit of performing reflection-based THz spectroscopy and by coulpling with metal tips, we can measure the electrical properties of nanostructures and even can perform the fine-resolution mapping.

✧ Mg-induced terahertz transparency of indium nitride films[13]

Terahertz time-domain spectroscopy (THz-TDS) has been used to investigate electrical properties of Mg-doped InN. Mg-doping in InN was found to significantly increase terahertz transmittance. THz-TDS analysis based on the Drude model shows that this high transmittance from Mg-doped InN is mainly due to the reduction in mobility associated with ionized dopants. The Hall-effect-measured mobility is typically lower than the THz-TDS-measured mobility for the same samples. However, the results of both measurements have the same slope in the linear relation between mobility and density. By introducing a compensation ratio of ~0.2, an excellent agreement in mobilities of two methods is obtained. This result can explain the discrepancy in the values of mobilites measured by THz spectroscopy and the Hall effect measurement and suggest the method to calibrated the result of Hall effect measurement.

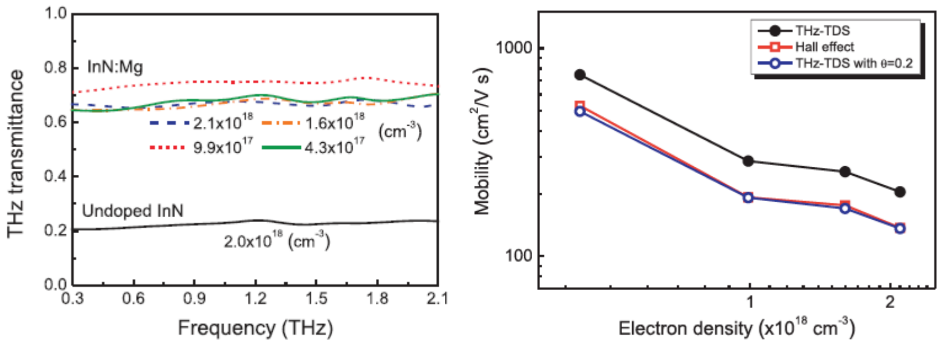

Fig. 10. (a) Terahertz transmittance of an undoped InN film and four Mg doped InN films with different carrier densities. (b)Electron-density-dependent electron mobility measured by the THz-TDS and the Hall-effect method. Blue circles are THz-TDS-measured mobility corrected by including a compensation ratio $\theta = 0.2$.

✧ **Background and photoexcited carrier dependence of terahertz radiation from Mg-doped nonpolar indium nitride films [3]**

Terahertz generation from Mg-doped nonpolar (*a*-plane) InN (*a*-InN:Mg) was systematically studied and compared with those from undoped *a*- and *c*-InN. While the amplitude and polarity of the THz field from Mg-doped polar (*c*-plane) InN depend on the background carrier density, the *p*-polarized THz field from *a*-InN:Mg has background carrier-insensitive intensity and polarity, which can be attributed to carrier transport in a polarization-induced in-plane electric field. A small but apparent azimuthal angle dependence of the THz field from *a*-InN:Mg shows the additional contribution of the second-order nonlinear optical effect. Meanwhile, in this study, we did not observe the contribution of the intrinsic in-plane electric field which is significant for high stacking fault density nonpolar InN.

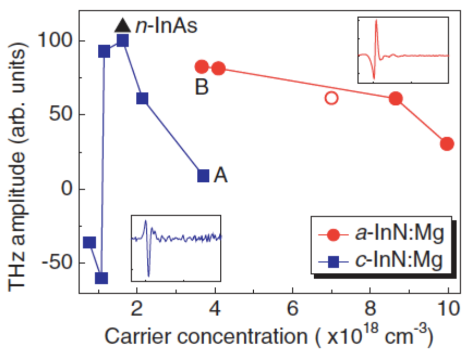

Fig. 11. Peak amplitudes of the THz radiation from Mg-doped *c*- (squares) and *a*-InN (circles) films as a function of background carrier concentration. The open circle indicates the peak amplitude obtained from an undoped *a*-InN and the solid triangle corresponds to an *n*-type InAs (100) with a carrier density of ~2×10^{17} cm^{-3}. The two insets in the figure illustrate the waveforms of THz radiation with positive and negative polarities, respectively.

✧ Carrier dynamics in InN nanorod arrays [14]

We investigated ultrafast carrier dynamics of vertically aligned indium nitride (InN) nanorod (NR) arrays grown by molecular-beam epitaxy on Si(111) substrates. Dominant band filling effects were observed and were attributed to a partial bleaching of absorption at the probe wavelengths near the absorption edge. Carrier relaxation in nanorod samples was strongly dependent on the rod size and length. In particular, a fast initial decay was observed for carriers in NRs with a small diameter (~30 nm), the lifetime of which is much shorter than the carrier cooling time, demonstrating the substantial surface-associated influence on carrier relaxation in semiconductor nanostructures.

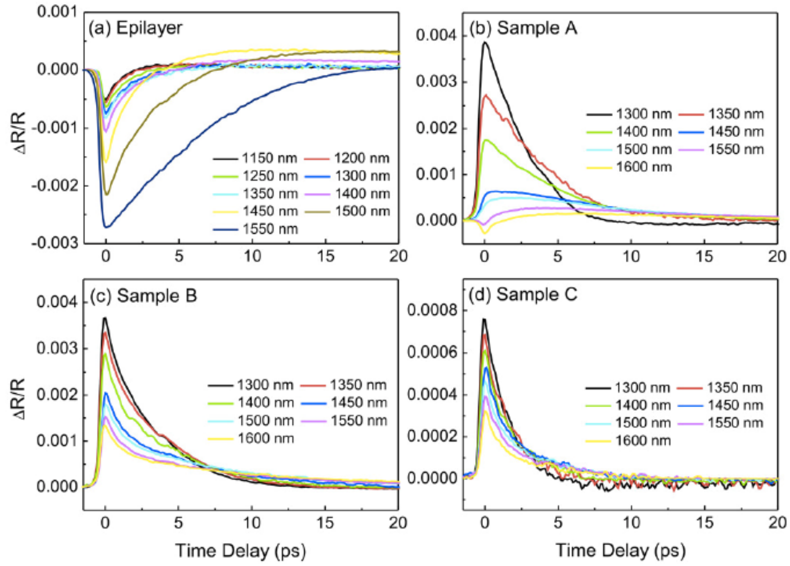

Fig. 12. Differential reflectivity transient of (a) InN epilayer and (b)-(d) NR samples A, B, and C measured at various probing wavelengths. Sample A with large rod diameter and long height has the sign flipping in $\Delta R/R$ as the probe wavelength increases beyond λ_c whereas sample B and C consisted of small diameter NRs have the positive change in $\Delta R/R$ for all probe wavelengths.

Curve fits to the measured data indicate that the wavelength-dependent cooling time τ_2 for InN film is of the order of 2 ps, which is similar to those for samples A and C. Figure 4(a) shows that the cooling time of sample B is comparable, but is relatively longer than those of other samples, the reason for which remains unclear. Here, it is worthy to note that in addition to τ_2, samples B and C have an initial rapid decay time τ_1 which is in the range of 500 fs to 1 ps. Because samples B and C are consisted of the 30-nm NRs, τ_1 is expected to be strongly correlated with the carrier confinement in the small NRs. For InN, surface electron accumulation layer extends to approximately 10 nm below the surface. For samples B and C, the electron accumulation layer is comparable to the radius of NRs (~15 nm) and subsequently, the photoexcited carriers can be easily trapped by the surface-related defects with a short lifetime.

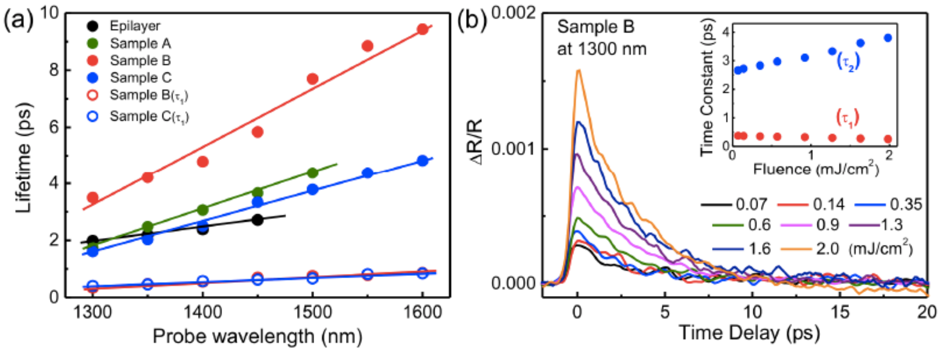

Fig. 13. (a) Carrier lifetimes of NR samples with different heights and diameters compared to that of epilayer film. Slow recombination time constants are not shown here. (b) Pump fluence dependence of differential reflectivity transient of sample B. Inset shows the carrier lifetimes τ_1 and τ_2 at the corresponding pump fluences.

✧ Terahertz emission mechanism of magnesium doped indium nitride [6]

The carrier concentration-dependence of terahertz emission from magnesium doped indium nitride (InN:Mg) films was investigated. It has been a main issue among the nitride research society to realize *p*-type InN to achieve p-n junction. In addition, the demonstration of embedded p-type layer below the narrow surface layer is another challenge. We investigated the terahertz emission mechanism of Mg-doped InN since the emission mechanism is based on the electron dynamics in the photoexcited area, holding the information of conduction type. Near the critical concentration ($n_c \sim 1\times10^{18}$ cm^{-3}), the competition between two emission mechanisms determines the polarity of terahertz emission. InN:Mg with $n > n_c$ exhibits enhanced positive-polarity terahertz emission compare to the undoped InN, which is due to the reduced screening of the photo-Dember field. For InN:Mg with $n < n_c$, the polarity of terahertz signal changes to negative, indicating the dominant contribution of the surface electric field due to the large downward surface band-bending within the sub-surface layer extending over the optical absorption depth.

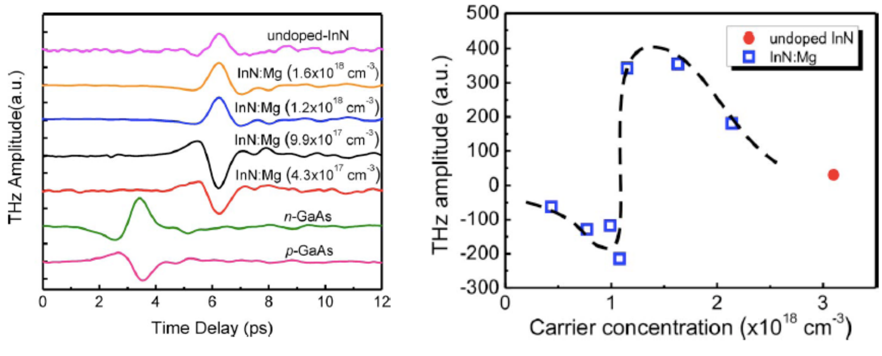

Fig. 14. (a) The time-domain terahertz waveforms of the as-grown (undoped) InN and Mg-doped InN films. InN:Mg films with the electron concentration below $\sim1\times10^{18}$ cm^{-3} have a negative

polarity, while others including undoped InN film have a positive polarity. The terahertz waveforms of *n*- and *p*-type GaAs are shown together for comparison. (b) The amplitude of terahertz emission field vs. pump fluence for InN:Mg films with n=4.3×10^{17} cm^{-3} and 1.6×10^{18} cm^{-3}. The sign of data of InN:Mg film with n=4.3×10^{17} cm^{-3} is inverted to be positive. Inset shows a typical azimuthal angle-dependent terahertz radiation from InN:Mg film.

✧ Carrier dynamics of Mg-doped indium nitride [4]

In our previous results, we have reported a significant enhancement (>500 times in intensity) in terahertz emission from Mg-doped indium nitride (InN:Mg) films compared to undoped InN. It was found that the intensity of terahertz radiation strongly depends on the background electron density. The carrier dynamics of InN:Mg is studied by employing ultrafast time-resolved reflectivity measurement. We find that the decay time constant of InN:Mg also depends on background electron density in the same way as terahertz radiation does as it shown in Fig. 16. The spatial redistribution of carriers in diffusion and drift is found to be responsible for the recombination behavior as well as terahertz radiation.

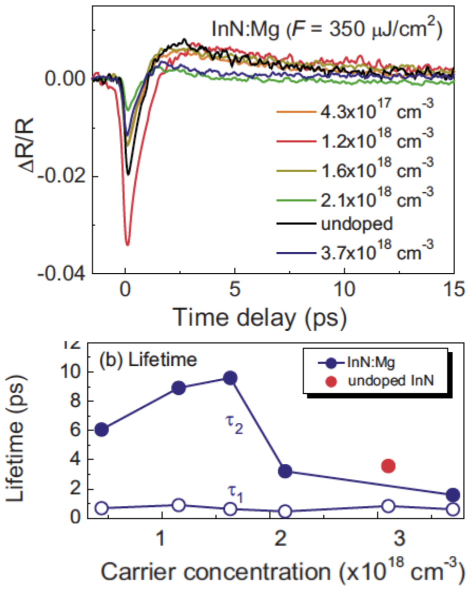

Fig. 15. Peak amplitudes of the THz radiation from Mg-doped *c*- (squares) and *a*-InN (circles) films as a function of background carrier concentration. The open circle indicates the peak amplitude obtained from an undoped *a*-InN and the solid triangle corresponds to an *n*-type InAs (100) with a carrier density of ~2×10^{17} cm^{-3}. The two insets in the figure illustrate the waveforms of THz radiation with positive and negative polarities, respectively.

✧ Plasmonic green nanolaser based on a metal-oxide-semiconductor structure[15]

Realization of smaller and faster coherent light sources is critically important for the emerging applications in nanophotonics and information technology. Semiconductor lasers are arguably the most suitable candidate for such purposes. However, the minimum size of conventional semiconductor lasers utilizing dielectric optical cavities for sustaining laser oscillation is ultimately governed by the diffraction limit (~(λ/2n)^3 for three-dimensional (3D) cavities, where λ is the free-space wavelength and n is the refractive index). Here, we demonstrate the 3D subdiffraction-limited laser operation in the green spectral region based on a metal_oxide_semiconductor (MOS) structure, comprising a bundle of green-emitting InGaN/GaN nanorods strongly coupled to a gold plate through a SiO_2 dielectric nanogap layer. In this plasmonic nanocavity structure, the analogue of MOS-type "nanocapacitor" in nanoelectronics leads to the confinement of the plasmonic field into a 3D mode volume of 8.0×10^{-4} μm^3 ($\sim 0.14(\lambda/2n)^3$). This laser is the smallest nanolaser ever demonstrated based on surface plasmonic coupling of lasing enhancement.

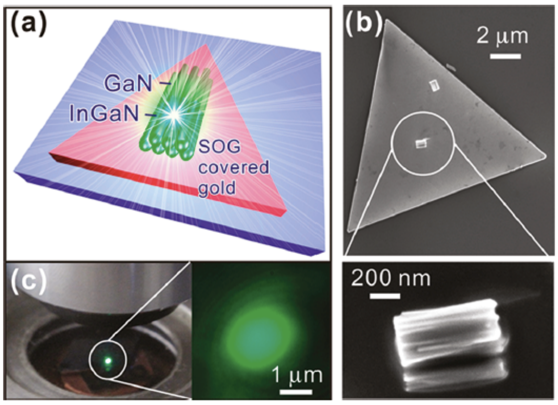

Figure 16. Plasmonic green nanolaser. (a) Schematic representation of the lasing MOS structure consisting of a bundle of green-emitting InGaN/GaN semiconductor nanorods, which is coupled to an underlying colloidal gold triangular plate through an SOG dielectric gap layer. The supporting substrate is silicon and the thickness of the SOG layer is about 5 nm. The average nanorod diameter is 30 nm, while the lengths of InGaN and GaN sections are 300 and 380 nm, respectively. (b) FE-SEM image of the hybrid system. The magnified image shows the detailed view of the measured InGaN/GaN nanorod bundle on top of the gold plate (c) The green laser emission from the InGaN/SOG/gold hybrid system in a cyrostat (at 7 K) and under the excitation of a frequency-doubled Ti:sapphire laser system

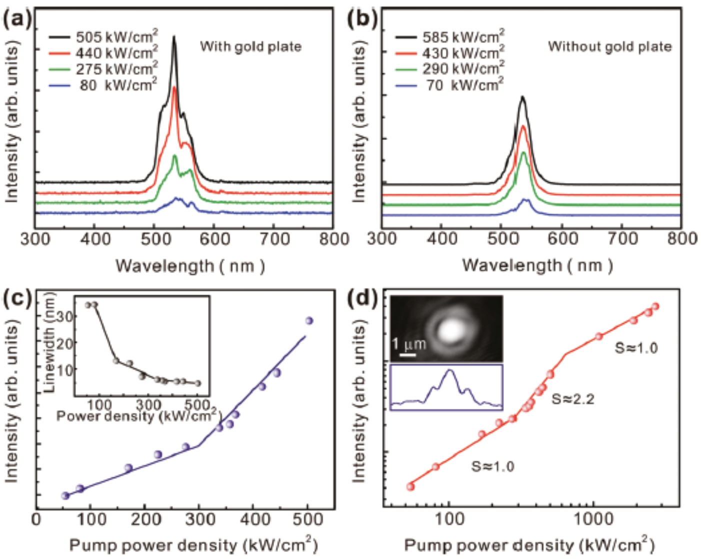

Figure 17. Lasing characteristics. (a) Power-dependent laser emission spectra of the InGaN/GaN nanorod bundle supported on the SOG covered gold plate. These spectra were recorded at 7 K with varying excitation intensities, showing the transition from spontaneous emission to lasing at 533 nm. (b) In comparison, the power-dependent photoluminescence spectra of the InGaN/GaN nanorod bundle directly positioned on an SOG/Si substrate (without the gold plate) show no signs of lasing. (c) For the lasing MOS structure, the superlinear response of the peak intensity becomes obvious when the excitation intensity is above the threshold intensity (~300 kW/cm2). The inset shows the simultaneous line width narrowing of the emission peak above the lasing threshold. (d) The complete lasing characteristics are shown as a log_log plot together with the corresponding slopes (S) for different regions. The inset shows the defocused lasing mode image. The appearance of the high-contrast fringes indicates spatial coherence due to lasing.

5. 文獻探討

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6. 計畫成果自評

Under the support of National Science Council, we have established a high-resolution terahertz imaging system, consisted of an inverted optical microscope and AFM manipulating system. With this system terahertz spectroscopy of highly absorbing and ultrathin materials can be investigated in the frequency of 0.3 – 2.2 THz. The signal-to-noise ratio of terahertz pulses is typically of the order of 10^6. Metal tip manipulation and sample rastering systems are installed and tested. The performance and the repeatability of the new terahertz spectroscopy system were checked by measuring the electrical properties of well-known materials including the InN film and Si wafer. Comparison of results with those measured by transmission-based terahertz spectroscopy system shows an excellent agreement. In order to demonstrate the prospect of newly established THz-reflection-TDS, we investigated the electrical properties of silver nanowires. Ag nanowires are designed to replace transparent conducting ITO sheet due to their high transparency and conductivity, but they have the intrinsic problem of oxidation. Thin oxide layer would hinder the electron transportation through the junction, but the influence of oxidation to the device performance has not been systematically studied and the results reported to date were obtained by the destructive method such as TEM imaging. By using THz-RTDS, we succeeded in measurement of electrical conductivity of Ag nanowires and the influence of natural oxidation on conductivity of Ag nanowires could be clarified. Since Ag nanowire layer is highly absorbing in terahertz range, it was extremely difficult to perform THz-transmission-TDS. And this demonstrates the feasibility of THz-RTDS on absorbing and also very thin materials.

We also performed ultrafast carrier dynamics study and time-domain THz spectroscopic study on semiconductors. A comprehensive investigation of carrier dynamics in the InN nanorod arrays was achieved by measuring the probe wavelength and polarization dependence of transient reflectivity. We observed abnormally short carrier relaxation time which is due to the fast trap of carriers by surface-associated defects in the very narrow nanorods. [**H. Ahn,*** C.-C. Yu, P. Yu, J. Tang, Y.-L. Hong, and S. Gwo, "Carrier dynamics in InN nanorod arrays," Opt. Exp. **20**, 769 (2012).] In the carrier dynamics study of Mg-doped InN, the decay time constant of InN:Mg depends on background electron density in the same way as terahertz radiation does. The spatial redistribution of carriers in diffusion and drift is found to be responsible for the recombination behavior as well as terahertz radiation. [**H. Ahn***, K.-J. Yu, Y.-L. Hong, and S. Gwo, "Carrier dynamics of magnesium doped indium nitride," Appl. Phys. Lett. 97, 062110 (2010).]

From the measurement of THz emission from Mg-doped c- and a-plane InN, we found that THz emission from Mg-doped InN is critically dependent on background carrier density. For Mg-doped c-plane InN, a transition of dominant terahertz emission mechanism between the photo-Dember effect and surface field acceleration occurs depending on the carrier concentration. [**H. Ahn***, Y.-J. Yeh, Y.-L. Hong, and S. Gwo, "Terahertz emission mechanism of magnesium doped indium nitride," Appl. Phys. Lett. **95**, 232104 (2009).] THz waves from *a*-InN:Mg and the polarity of these waves are background carrier-insensitive, which can be attributed to carrier transport in a

polarization-induced in-plane electric field. [**H. Ahn***, Y.-J. Yeh, Y.-L. Hong, and S. Gwo, "Background and photoexcited carrier dependence of terahertz radiation from Mg-doped nonpolar indium nitride films," Appl. Phys. Express 3, 122105 (2010).]
Optical emission mechanisms of semiconductor nanostructures have been studied by measuring time-integral and time-resolved photoluminescence. We first measured the strong green PL from InGaN/GaN nanorods and found that the enhancement of the green light emission from epitaxially-grown InGaN nanorods is due to the radiative recombination of deeply localized excitions associated with the increased composition non-uniformity in the nanorods. [C.-C, Hong, **H. Ahn***, C.-Y. Wu, and S. Gwo, "Strong green photoluminescence from $In_xGa_{1-x}N$/GaN nanorod array," *Optics Express* **17**, 17227 (2009)] The enhancement of light emission from the same InGaN nanorods was achieved by coupled to a gold plate through a SiO2 dielectric nanogap layer. And finally, the 3D sub-diffraction-limited laser operation in the green spectral region based on a metal_oxide_semiconductor (MOS) structure could be realized. [C.-Y. Wu, C.-T. Kuo, C.-Y. Wang, C.-L. He, M.-H. Lin, **H. Ahn,*** and S. Gwo,* "Plasmonic green nanolaser based on a metal–oxide–semiconductor structure," Nano Lett. **11**, 4256 (2011).] Following work of our nanolaser demonstrating the remarkable enhancement of laser intensity and the reduction of threshold energy were recently published in the Science journal.

Through this project 9 SCI papers were published in high-IF journals including Nano Letters, Applied Physical Letters, Optics Express, and Applied Physics Express and 3 conference proceedings. 6 international conference papers have been presented in world-leading conferences in optoelectronic fields, such as CLEO, SPIE/OPTO, and Material Research Society meeting and two papers will be presented in Frontiers of Optics and 2013 SPIE/OPTO next January. 9 domestic conferences papers were presented in OPT and Chinese Physics Society meeting. In particular, I was invited to SPIE Photonic West 2011 and MRS 2009 Fall meeting.

The series of work on InN we have studied by using THz spectroscopy not only became a milestone in better understanding of InN property itself, but also opened the potential of InN in near-infrared and THz frequency applications. Our papers began to be recognized by several important papers. In particular, the success of identification of THz emission from nonpolar InN film was cited as an important achievement in THz application. Papers regarding terahertz emission mechanism of Mg-doped InN [Appl. Phys. Lett. **95**, 232104 (2009)] and green PL from InGaN nanorods [Opt. Express **17**, 17227 (2009)] have already been cited 10 and 14 times, respectively.

■ **指導學生獲獎或學術競賽獎**

(1)碩士學生葉苡柔 2009 **臺灣物理學會年會**獲得壁報論文佳作獎

(2)學生李珉澤獲得國科會 99 年度「**大專學生參與專題研究計畫**」核定

(3)學生李珉澤獲得中國工程師學會學生分會 100 年度「**工程論文競賽優等獎**」

(4)碩士學生賈智爲獲得 2010 臺灣光電科技研討會國科會光電學門成果發表會「**優良論文獎**」

(5)碩士學生劉東閔 2012 **臺灣物理學會年會**獲得壁報論文佳作獎

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[1] **H. Ahn,*** M.-T. Lee, Y.-M. Chang, and S. Gwo, "Nonlinear absorption in InN under resonant- and non-resonant excitation," 8615-18, OPTO 2013, SPIE Photonic West, February 2-8, 2013, San Francisco, U.S.A.

[2] H.- M. Lee, J.-W. Chia, **H. Ahn,*** Y.-L. Hong, and S. Gwo, "Terahertz time-domain spectroscopy studies of Mg-doped InN," 2011 MRS Fall meeting, MRS symposium I: III-nitride materials for sensing, energy conversion, and controlled light-matter interactions, Nov. 28 - Dec. 2, 2011, Boston U.S.A.

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[6] **H. Ahn***, Y.-J. Yeh, Y.-L. Hong, and S. Gwo, "THz study on InN," 2009 MRS Fall meeting, MRS symposium I: III-nitride materials for sensing, energy conversion, and controlled light-matter interactions, Nov. 30 - Dec. 4, 2009, Boston U.S.A. (Invited speaker).

Domestic conference papers

[1] Y.-S. Liou, H.-M. Lee, Y.-L. Hong, S. Gwo, and H. Ahn, "Temperature dependence of photoluminescence from InN nanorods," 2012 Annual Meeting of the Physical Society of Republic of China.

[2] T.-M. Liu, C.-C. Yu, Y.-L. Hong, S. Gwo, and H. Ahn, "Carrier dynamics of indium nitride nanorod arrays," 2012 Annual Meeting of the Physical Society of Republic of China.

[3] C.-Y. Chang, C.-W. Chia, H.-M. Lee, S. Gwo, and H. Ahn, "Coherent THz Spectroscopic Study of *A*-plane InN Film," Optics and Photonics in Taiwan, Tainan, Taiwan (2011).

[4] H.-M. Lee, J.-W. Chia, C.-Y. Chang, and S. Gwo, H. Ahn, "Electrical conductivity anisotropy of a-plane InN," Optics and Photonics in Taiwan, Tainan, Taiwan (2011).

[5] C.-C. Yu, H. Ahn, Y.-L. Hong, and S. Gwo, "ultrafast carrier dynamics of magnesium doped indium nitride," 2011 Annual Meeting of the Physical Society of Republic of China.

[6] Y.-M. Chang, M.-H. Lin, H.-M. Lee, S. Gwo, and H. Ahn, "Nonlinearity of Gold Nanoparticle Crystal," 2011 Annual Meeting of the Physical Society of Republic of China.

[7] C.-W. Jia, H.-M. Lee, S. Gwo, and H. Ahn, "Coherent Terahertz Spectroscopic Study of Mg-doped InN," Optics and Photonics in Taiwan, Tainan, Taiwan (2010).

[8] J.-J. Chen, H. Ahn, R.-H Shu, T.-A. Liu, and J.-L. Peng, "All-Normal Dispersion Mode-locked Ytterbium Fiber Laser," 2010 Annual Meeting of the Physical Society of Republic of China.

[9] Y.-J. Yeh, H. Ahn, Y.-L. Hong, and S. Gwo, "Terahertz Emission Mechanism of *c*-plane and *a*-plane Magnesium Doped Indium Nitride," 2010 Annual Meeting of the Physical Society of Republic of China.

出席國際學術會議心得報告

計畫編號	NSC 98-2112-M-009 -009 -MY3
計畫名稱	NSC 98-2112-M-009 -009 -MY3
出國人員姓名 服務機關及職稱	安惠榮，副教授，國立交通大學光電系
會議時間地點	May 16 –22, 2010, San Jose, USA
會議名稱	CLEO/IQEC 2010
發表論文題目	“Terahertz Emission of Magnesium doped Indium Nitride”

Conference on lasers and electro-optics (CLEO)/Quantum electronics and laser science congerence (QELS) is one of the main international conference in optics/laser-related field. Since its first appearance in 1980s, the number of contributed papers in THz research related field kept increasing and with no surprise, there were THz-related sessions at least for good three days (from morning to afternoon sessions) among five day-long conferece. The fields include THz emission, detection, spectrocopy, waveguide, imaging, metamaterials, etc so that one can immediatedly see the prospects and the importantce of THz research in current optics society.

May 17 (Monday)

There were four THz-related sessions; THz detection (CMF), Intense THz phenomena (CMP), THz domain spectroscopy (CMZ), and THz ultrafast generation (CMJJ). And my student gave an oral presentation in CMJJ session under the title of “Terahertz Emission of Magnesium doped Indium Nitride” (CMJJ4). In this presentation, we reported the dramatic enhancement of THz intensity (more than 500 times) from Mg-doped InN compared to that from undoped ones. Our result shows the highest THz intensity enhancement ever obtained from InN. In the same session, there was a talk on “Intense terahertz generation based on the photo-Dember effect” presented by Univ. of Kostanz, Germany. The idea of THz enhancement is very simple and similar to our precious result presented in CLEO last year, which is the rotation of photo-Dember field to increase the light extraction from semiconductor THz emitter. I believe we can try the similar experiment based on metal nanoparticles which can locally rotate the direction of electric field along the surface. A paper on THz spectroscopy of single-walled carbon nanotube also attracted my attention since it can be used as a THz polarizer with higher extinction ratio. CMP5 presented THz nonlinearity of water induced by intense THz pulses which is generated by ultrashort pulse and $LiNbO_3$ crystal. We are also interested in developing intense THz pulse sources for time-resolved THz spectroscopy and nonlinear optical application so that the session CMP was very useful to gather the valuable information.

May 18 (Tuesday)

There were also four THz-related sessions in this day; THz metamaterials (CTuF), THz waveguides (CTuQ), nonlinear and linear THz spectroscopy (CTuBB), and THz quantum cascade lasers (CTuMM). CTuBB2 under the title of “Ultrafast Broadband Mid-Infrared Pump, Terahertz Probe Spectroscopy” reminded us to accelerate the development of broadband light source in our lab by using OPA which can extend our time-resolved ultrafast spectroscopy research capability to broader areas. "Concentration of Terahertz Radiation Through Tapered Circular Subwavelength Apertures" (CTuF2) is a simple result based on tapered metal waveguide to enhance THz enhancement. They also observed the decrease of group velocity so that it can be applied to study slow light research. "Chiral THz Metamaterial with Tunable Optical Activity" (CTuF6) demonstrated the possibility of generation of THz radiation with circular polarization which can be crucial in bio- and medical application.

May 19 (Wednesday)

There was an important session on THz imaging (CWO) since our NSC project is related with THz near-field imaging. There were 7 presentations of experimental and theoretical works. "Near-field microscopy of thermal radiation" adopted a charge sensitive phototransistor to image spontaneously emitted thermal radiation and it can be applied to observe mesoscopic phenomena such as molecular motions, biomolecular protein interactions, and semiconductor conditions in the future. "High-speed hand-held wide aperture time-domain terahertz imaging system" (CWO1) introduced a commercial hand-held, TD-THz reflection line-scanner developed by Picometrix. Actually the product is quite bulky and cannot be called as a hand-held instrument, but it was innovative to integrated TD-THz system as an image scanner. "Terahertz emission from optical fiber tip and near-field microscope applications" (CWO2) presented an optical fiber tip coated with InAs thin film illuminated by guided laser field and achieved λ/20 sub-wavelength imaging in an InAs-based transmissive near-field laser emission THz microscope. It was a simple and neat idea to couple the THz emitting semiconductor on the optical fiber tip to achieve near-field study. It is quite similar idea to our sandwitch configuration of near-field imaging method we are pursuing in our project. "Surface Energy Transport following Relativistic Laser-Solid interaction" (JWC2) was presented my supervisor, Prof. M. C. Downer which shows runaway electrons and strong magnetic fields govern fs surface heating observed from Al target excited at 3E18 W/cm^2.

May 20 (Thursday)

In the talk of "Nano-coupling and enhancement in plasmonic conical needle experiments" (QThH2), efficient coupling and power concentration of radially-polarized light in conical plasmonic needle is presented. Needle length dependent resonances are calculated. Radial plasmonic DBR with needle as defect was fabricated for NSOM and nonlinear conversion. An invited talk (QThB1) was given by Prof. Shalaev in Purdue Univ. in which he reviewed the fundamentals of metamaterials and suggested new applications ranging from a planar hyperlens to optical black hole. "Integrated Terahertz pulse generation and amplification in quantum cascade lasers" (CTuU6) demonstrated that THz pulses can be directly generated on the THz QCL by illuminating the QCL facet with a femtosecond near-infrared laser. "Terahertz time domain spectroscopy of phonon-depopulation based quantum cascade lasers" (CThU3) showed that broadband THz probe pulses can be coupled into the laser cavity and the detection of the transmitted pulses is used to determine the spectral gain of THz QCLs.

Due to the flight schedule, I left to San Francisco on Thursday.

It was very clear that the THz science and technology is the emerging field in optoelectronic fields. In particular, recent fast development of strong THz light source makes it possible to use THz waves to photoexcite materials, not only to use it as weak probe. In this conference several new schemes were proposed to generate intense as well as broadband THz radiation. In order to study the fine structure spectroscopy and time-resolved excitonic spectroscopy, it is essential to have intense THz pump source. Currently THz radiation sources in my lab are still far too weak to be used for photoexcitation. Time-domain spectroscopy requires more powerful and broadband light source which can pinpoint the energy transition. Therefore, in the near future, we will pursue the development of new and simple method to perform THz pump-optical/THz probe measurement.

CLEO also celebrated the 50th anniversary of laser invention and there was a small exhibition of the history of laser development, including the first ruby laser demonstrated in 1960.

國科會補助專題研究計畫項下出席國際學術會議心得報告

日期：100 年 3 月 27 日

計畫編號	NSC 98－2112－M－009－009－MY3		
計畫名稱	近場兆赫頻波光譜研究		
出國人員姓名	安惠榮	服務機構及職稱	副教授, 國立交通大學光電系
會議時間	100 年 1 月 23 日到 100 年 1 月 23 日至	會議地點	San Francisco, USA
會議名稱	(中文) (英文) SPIE Photonic West 2011		
發表論文題目	(中文) (英文)“Carrier dynamics of Mg-doped indium nitride” “Terahertz emission from Mg-doped a-plane InN”		

一、參加會議經過

Jan. 23: Arrival and registration
Jan. 24 – Jan.28: Attend conference
Jan. 28: Return

二、與會心得

I attended 2011 SPIE Photonic West held in San Francisco and presented two oral talks in two different session. One of them was an invited talk under the title of “Carrier dynamics of Mg-doped indium nitride” in the session of Ultrafast Phenomena and Nanophotonics. The other was a distributed talk under the title of “Terahertz emission from Mg-doped a-plane InN”. These two results were published in Applied Physics Letter and Applied Physics Express, respectively.

January 24 (Monday)

My two talks were scheduled on Monday. In the morning, I gave a talk in the session of Quantum Sensing and Nanophotonic Devices VIII. This session is mainly arranged with the paper of sensors and devices and terahertz wave surface plasmonic wave are the two newly emerging wavelength sources for device development. Therefore, two morning session were dedicated to THz and plasmonics devices and I presented our recent result on THz emission from magnesium doped a-plane InN. Strong THz emission comparable to THz emission from InAs was demonstrated from Mg-doped c-plane InN last year by our group and this talk was about different THz emission mechanism from a-plane InN which is as intense as that from c-plane InN, but does not depend on the carrier density. This result eases the growth condition of InN films for device development.
In the afternoon session of Ultrafast Phenomena and Nanophotonics, I gave an invited talk on carrier dynamics of Mg-doped InN. In this talk, the details of carrier dynamics of InN:Mg which is crucial for the clarification of the terahertz emission mechanism were

investigated by performing the time-resolved optical reflectivity measurement.

Jan. 25 (Tuesday)

Three plenary talks were given in the morning in OPTO session. A talk given by K. D. Kim from LG Display R&D center was about current and future development of e-paper and flexible display. This field of research is closely related with the researches in my department, including Display center and liquid crystal labs so that it was very interesting for me to learn about the overview and roadmap of flexible display application. One of the inventors of photonic crystal, Prof. Yablonovitch also gave a plenary talk on the metal optics addressing the conflict between micro electronics and optical plasmonics. Although it was my second time to listen his presentation, it was interesting enough by adding a new theoretical works developed in plasmoncs. In the session of photonic metamaterials, there was an invited talk on metamaterials based on graphene. After Nobel prize was given to graphene last year, this material has received great attention in many different fields and in the 2D metamaterials field, it plays an important role. Enhancement of transmission through subwavelength aperture was demonstrated in both optical and THz wavelength range in several papers.

Jan. 26 (Wednesday)

In the session of Photonic and Phononic Properties of Engineered Nanostructures, many interesting talks and posters were presented on photonic crystals and metamaterials. In the talk of "Investigation of the nonlinear optical response from arrays of Au bowtie nanoantennas", nonlinear properties of Au nanoantennas were presented. Since we are currently working on the nonlinear properties of 3D Au nanoparticle crystals, this talk was quite interesting to me.

In the Monday session of Advances in Slow and Fast Light IV, a talk under the title of "Three-dimensional plasmonic metamaterials for slow light propagation at visible frequencies Nanostructures" was given by my collaborator group in Tsing Hua University. The target material was the same 3D Au nanoparticle crystal and its plasmonic properties, especially at least 30 times of slow-down of light velocity were presented. As an extension of this work done in visible range, we are planning to investigate the slow light propagation in THz range.

Jan. 27 (Thursday)

In the session of Gallium Nitride Materials and Devices VI, an invited talk was given under the title of "InGaN/GaN nanorod light-emitting diodes as white and full-colorlight sources". This talk demonstrated the bright white light emission from nitride nanorods, which overcame the problem of blue-green gap of nitride-based LED. This result also demonstrated the smallest white light source in nanometer scale. There was one-day session of Terahertz Technology and Applications. Since THz wave becomes one of the available light source for many different applications, many THz wave-related papers were presented in various session and THz technology session becomes relative small. I believe it is a positive phenomena which demonstrates the importance of THz wave and it also indicates that the researches and techniques are already well developed to be applied to other fields. THz imaging and device development. In a talk given by Slingerland et al., a different methods for measuring spectroscopic lines, using an FTIR spectrometer or an FIR laser in conjunction with a Schottky diode mixer, were presented along with representative data collected from these systems. These measurements highlight the benefits of each spectroscopic system along with the type of data that can be collected from them.

It was very clear that the THz science and technology is the emerging field in optoelectronic fields. After the presentation of carrier dynamics study of InN, there was a critic on our work claiming that what we observed with 800 nm probe pulse would only demonstrate the bandfilling effect due to the increase of defects during the growth of Mg-doped InN. This question was raised because a single wavelength of probe was used in this work, which is way higher than the bandgap energy of InN. I believe this would be a key point in analysis of InN which may have high defect density. After this trip, we immediately increased the probe wavelength range with OPA from 800 nm to 1600 nm so that we can observe the wide range carrier dynamics of InN. Therefore, despite of critics, it became a important trip for our current researches, not only in ultrafast carrier dynamics study and but also THz spectroscopy and imaging.

四、建議

五、攜回資料名稱及內容

Conference program