行政院國家科學委員會專題研究計畫 成果報告

低夾止漏電流變晶式高電子遷移率電晶體之分子束磊晶與光偵測響應特性

研究成果報告(精簡版)

計畫類別：個別型
計畫編號：NSC 94-2218-E-018-003-
執行期間：94年12月01日至95年10月31日
執行單位：國立彰化師範大學電子工程學系

計畫主持人：吳正信

計畫參與人員：碩士班研究生-兼任助理：曾瑞賢、劉振邦、柯順祥

處理方式：本計畫涉及專利或其他智慧財產權，1年後可公開查詢

中華民國 96年01月31日

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

低夾止漏電流變晶式高電子遷移率電晶體之分子束磊晶與光偵測響應特性
(MBE technology and photodetection response characteristics of low pinch-off leakage metamorphic high-electron-mobility transistors)

計畫類別：■ 個別型計畫 □ 整合型計畫
計畫編號：NSC 94－2218－E－018－003－
執行期間：94 年 12 月 01 日 至 95 年 10 月 31 日

計畫主持人：吳正信
共同主持人：
計畫參與人員：曾瑞賢、劉振邦、柯順祥

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

本成果報告包括以下應繳交之附件：
□赴國外出差或研習心得報告一份
□赴大陸地區出差或研習心得報告一份
□出席國際學術會議心得報告及發表之論文各一份
□國際合作研究計畫國外研究報告書一份

處理方式：除產學合作研究計畫、提升產業技術及人才培育研究計畫、列管計畫及下列情形者外，得立即公開查詢
□涉及專利或其他智慧財產權，■一年 □二年後可公開查詢

執行單位：國立彰化師範大學電子系

中 華 民 國 96 年 1 月 31 日

一、摘要：

本計畫特別針對變晶式高電子遷移率電晶體的夾止漏電流特性，探討分子束磊晶成長的溫度、成長速率、與 V/III 比所造成的影響。我們以多種的分析技術測試磊晶材料的特性，包括光致激光、原子力顯微鏡、X 光倒晶格映像、Hall 量測以及變晶式緩衝層電流-電壓特性曲線等。最後磊晶成長並製作完成電晶體元件，g_m 值為 340 mS/mm，優異的夾止特性使得 I_{ON}/I_{OFF} 比值達到 10^6。

This proposal has been aimed at exploring the effects of the MBE growth conditions, including growth temperature, growth rate and V/III ratio, on the pinch-off leakage characteristics of mHEMTs. Various measurement technologies, including PL, AFM, x-ray RSM, Hall measurement, and I-V characteristics of the metamorphic buffer layer, have been used to characterize the epitaxial materials. Finally the mHEMT epi wafer has been grown and fabricated into devices. Results show g_m of 340 mS/mm and excellent pinch-off characteristics which gives a I_{ON}/I_{OFF} ratio as high as 10^6.

關鍵詞：

變晶式高電子遷移率電晶體
(metamorhpic high-electron mobility transistor; mHEMT)
夾止漏電流
(pinch-off leakage)
分子束磊晶成長
(molecular beam epitaxy; MBE)
X 光倒晶格映像
(x-ray reciprocal space mapping; x-ray RSM)

二、前言：

InAlAs/InGaAs metamorphic high electron mobility transistors (mHEMTs) on GaAs substrates have attracted much attention recently [1-3] because this technology combines the excellent high-frequency and low-noise performances inherent in InP-based HEMTs with the lower cost, larger wafer size, less fragility, and more mature processing of GaAs substrates. Besides, the indium composition of the InGaAs channel material can be freely chosen to meet the specific requirements of high-speed operation or high breakdown characteristics [4-6].

The pinch-off leakage denotes the minimum current conducted in a HEMT device which is operated at the subthreshold regime. It is one of the most important HEMT device parameters, since it represents how perfectly the HEMT device stays at the OFF state. High pinch-off leakage can cause harmonic distortion and noise in a high-speed low-power RF circuit. The pinch-off leakage can be affected by several factors, including the transistor structure, device processing, and epitaxial quality. On the epi-growth side, the metamorphic buffer layer (MBL), which is needed to accommodate the dislocations caused by the lattice mismatch between GaAs and InAlAs, plays a crucial role in obtaining high quality mHEMT epitaxy.

三、研究目的：

In this project, we plan to examine the influence of the MBL growth conditions (temperature, growth rate, and V/III ratio) on the epilayer quality using optical microscopy (OM), photoluminescence (PL), atomic force microscopy (AFM), Hall mobility, x-ray reciprocal space mapping (RSM), and I-V leakage test of a buffer structure. Adopting the optimal growth conditions, we fabricate InAlAs/InGaAs mHEMT devices with excellent pinch-off characteristics.

四、研究方法：

For the implementation of this project, some epi structures have been designed and grown by solid-source molecular beam epitaxy (MBE) on (100)-oriented semi-insulating GaAs substrates.

The MBL test structure consists of a 1-µm inverse-step linearly-graded $In_xAl_{1-x}As$ MBL with the indium content varying from 0.01 to 0.62, followed by a 300-nm $In_{0.52}Al_{0.48}As$ buffer layer and a 2-nm $In_{0.53}Ga_{0.47}As$ cap layer. Different growth temperatures (380, 400, 420, and 440 ^{o}C) were used for the $In_xAl_{1-x}As$ MBL in different samples, while the growth temperature for both the $In_{0.52}Al_{0.48}As$ buffer layer and the $In_{0.53}Ga_{0.47}As$ cap layer was kept at around 500 ^{o}C. The mHEMT device structure additionally includes, upon the above mentioned 1-µm $In_xAl_{1-x}As$ MBL and 300-nm $In_{0.52}Al_{0.48}As$ buffer layer, a 15-nm $In_{0.53}Ga_{0.47}As$ channel layer, a 5-nm $In_{0.52}Al_{0.48}As$ spacer layer, a Si delta doping layer, a 10-nm $In_{0.52}Al_{0.48}As$ Schottky layer, and a 20-nm Si-doped $In_{0.53}Ga_{0.47}As$ cap layer, all grown at 500 ^{o}C. The capless mHEMT structure for Hall measurement is the same as the full mHEMT device structure except that the cap layer is only 5 nm thick. In addition to the temperature effect, two different growth rates (0.7 µm/hr and 1 µm/hr) and various V/III ratios have also been tested.

The MBL test structure was characterized by several techniques, including OM, PL, AFM, and buffer leakage test. For the buffer leakage test, Ni/Ge/Au was deposited and annealed for ohmic contacts of two probe electrodes, and the distance between these two contacts was 150 µm. Hall measurement was employed to check mobility and carrier concentration of the capless mHEMT structure. X-ray RSM has also been performed for the mHEMT device structure.

As for device fabrication, conventional photolithography, liftoff, and annealing were employed. $H_3PO_4/H_2O_2/H_2O$ solution was used for mesa etching. Ni/Ge/Au was used for source and drain ohmic contacts. Selective gate recessing was performed using the succinic acid-based solution, and Au was used as the gate metal. The gate length and width were 1.1 µm and 110 µm, respectively, and the source-to-drain space was 5 µm.

五、結果與討論：

Fig. 1 shows the OM surface morphology of the epiwafers with the $In_xAl_{1-x}As$ MBL grown at 380 ^{o}C (left) and at other higher temperatures (right). Too low temperatures (less than 380 ^{o}C) give rise to a amorphous-like surface, while cross-hatching surface caused by lattice mismatch can be seen for other higher temperatures.

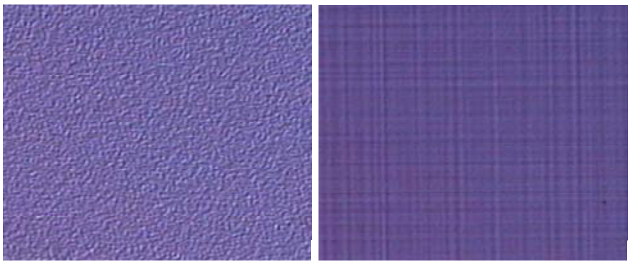

Fig. 1 Surface morphology of the epiwafers for the MBL grown at 380 ^{o}C (left) and other higher temperatures (right) .

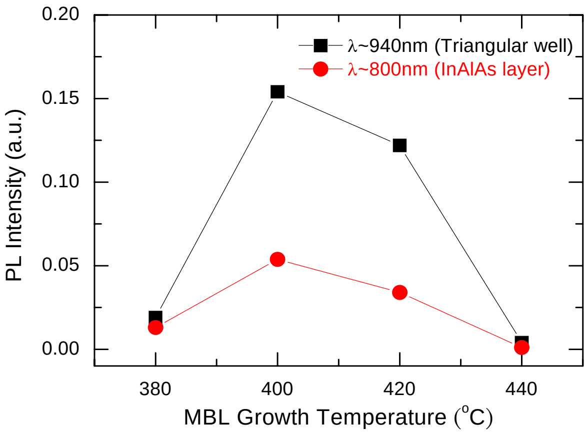

Fig. 2 PL intensity for various MBL growth temperatures

A triangular quantum well is formed at the interface of the upper end of the metamorphic InAlAs layer (where the indium content reaches 0.62) and the lower end of the 300-nm $In_{0.52}Al_{0.48}As$ buffer. The PL intensities from this triangular well and the $In_{0.52}Al_{0.48}As$ buffer layer for different MBL growth temperature are shown in Fig. 2. It's noticed that the PL from the triangular well has higher intensity than that from the bulk $In_{0.52}Al_{0.48}As$ buffer layer, presumably due to the quantum confinement effect. The PL has the maximum intensity at the growth temperature of 400 °C. For higher temperatures, the PL intensity weakens although the OM surface morphology shows no observable difference.

AFM data indicate the smallest root-mean-square (RMS) surface roughness of about 3.3 nm for the MBL growth temperature at 400 °C, as shown in Fig. 3 (solid square). The amorphous-like surface for MBL growth temperature at 380 °C has the highest RMS roughness of 5.3 nm. Fig. 3 (solid triangle) also shows the buffer leakage current estimated on the MBL test structure. The leakage current is defined at the applied voltage of 10 volt (across the contact electrodes separated by 150 μm). It's found that the buffer leakage varies greatly. The MBL growth temperature of 400 °C gives the lowest buffer leakage current, while 380 °C causes the leakage dramatically high.

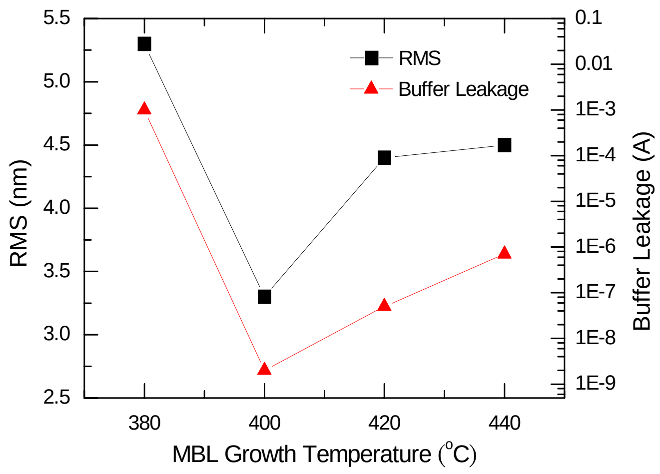

Fig. 3 Dependences of AFM RMS roughness and buffer leakage on the MBL growth temperature.

For the mHEMT structure, the dependence of mobility on the MBL growth temperature is shown in Fig. 4. We can see that the mHEMT structures grown with the MBL growth temperature above (including) 400 °C exhibit similar mobility of around 8700 ~ 9000 cm^2/V-s. The Hall carrier concentrations for these samples are about 3×10^{12} cm^{-2}. The amorphous-like sample shows a very poor mobility. The results of buffer leakage and Hall mobility indicate the best MBL growth temperature of 400 °C in this work for the growth of high-speed and low-leakage mHEMTs.

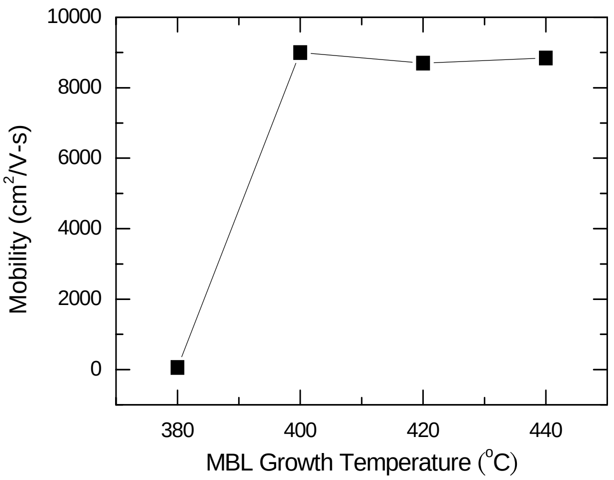

Fig. 4 Hall mobility obtained for samples with MBL grown at different temperatures.

The mobility as a function of the 2DEG concentration reveals different results for two different growth rates (0.7 μm/hr and 1 μm/hr). It's clearly seen that a lower growth rate leads to a higher mobility, as shown in Fig. 5.

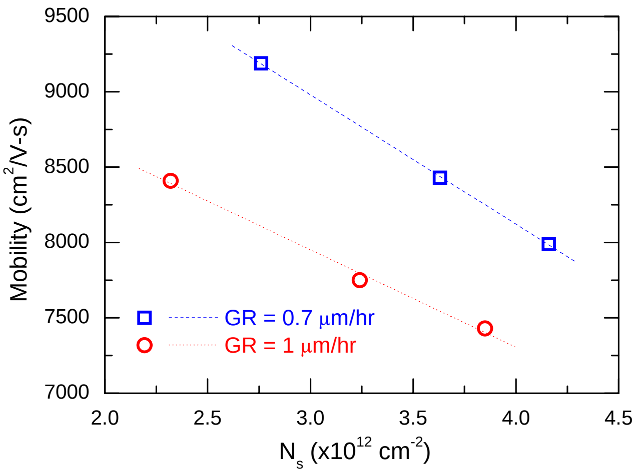

Fig. 5 Hall mobility as a function of the 2DEG concentration for different MBL growth rates.

Fig. 6 shows the pinch-off leakage of the mHEMT devices with different V/III ratios used for MBL growth. We can see that a lower V/III ratio tends to give lower pinch-off leakage. However, if the V/III ratio is too low, the arsenic supply becomes insufficient, resulting in group III-rich growth and amorphous material.

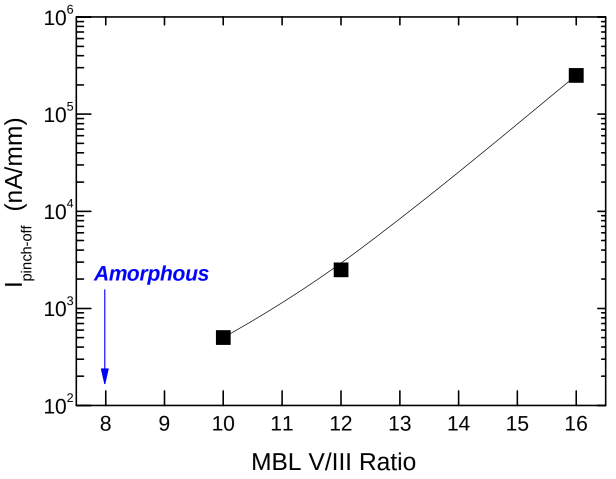

Fig. 6 mHEMT device pinch-off leakage for different MBL V/III ratio.

Typical current-voltage (I-V) and transfer characteristics of the mHEMT devices grown with optimal growth conditions are presented in Fig. 7. The device shows a maximum extrinsic transconductance (g_m) of 340 mS/mm. The ratio of I_{ON}/I_{OFF} is as high as 10^6, indicating a very good pinch-off characteristics.

X-ray reciprocal space mapping (RSM) has been performed for the mHEMT epi material, as shown in Fig. 8. The sharpest and most intense peak is from the GaAs substrate, while a broader, not-as-intense bump corresponds to the upon-MBL $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HEMT device structure. A wide, plateau-like background is due to the 1 μm-thick MBL which has the indium composition varying from 0.01 to 0.62.

六、結論：

The influence of the MBL growth conditions on the epilayer quality of metamorphic heterostructures and mHEMT has been investigated using various characterization techniques. Experimental results indicate that the best MBL growth temperature to achieve as-low-as-possible leakage is about 20 °C higher than a specific temperature point where the epiwafer commences showing an amorphous-like surface. For higher MBL growth temperatures, the buffer leakage performance can be degraded, even though Hall mobility keeps uninfluenced. Besides, a lower growth rate leads to high mobility. mHEMT devices with low pinch-off leakage has also been demonstrated. X-ray RSM measurement has ben performed for the mHEMT epi material to check the scenario of the In composition distribution.

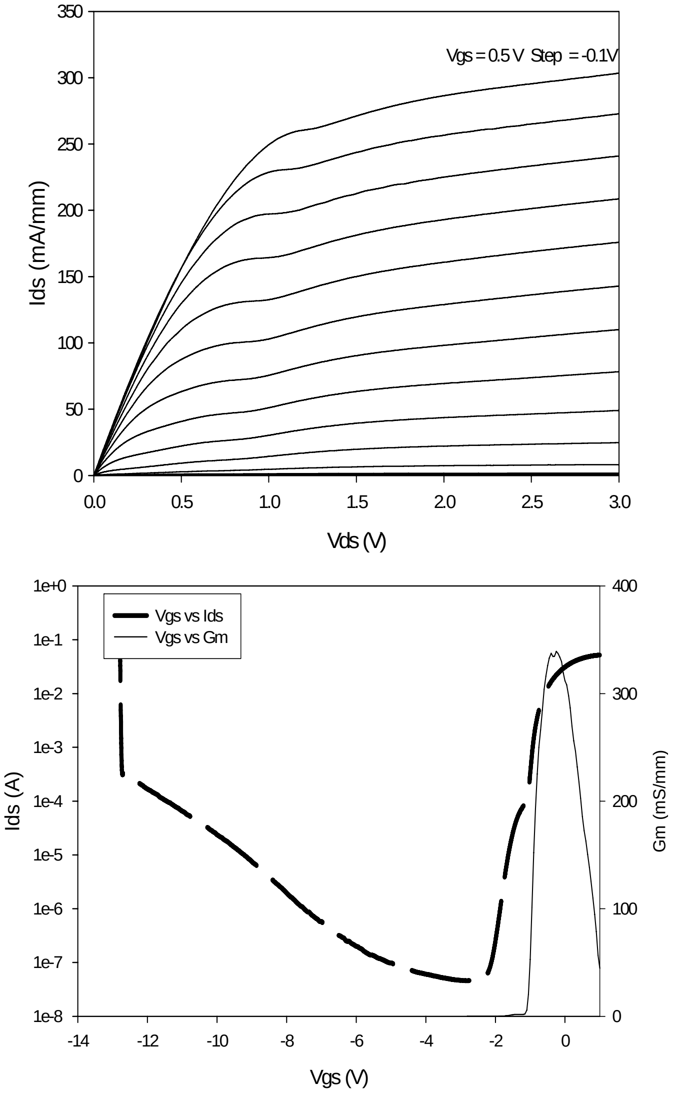

Fig. 7 Typical I-V (upper) and transfer (lower) characteristics of the mHEMTs with MBL grown at optimal growth conditions.

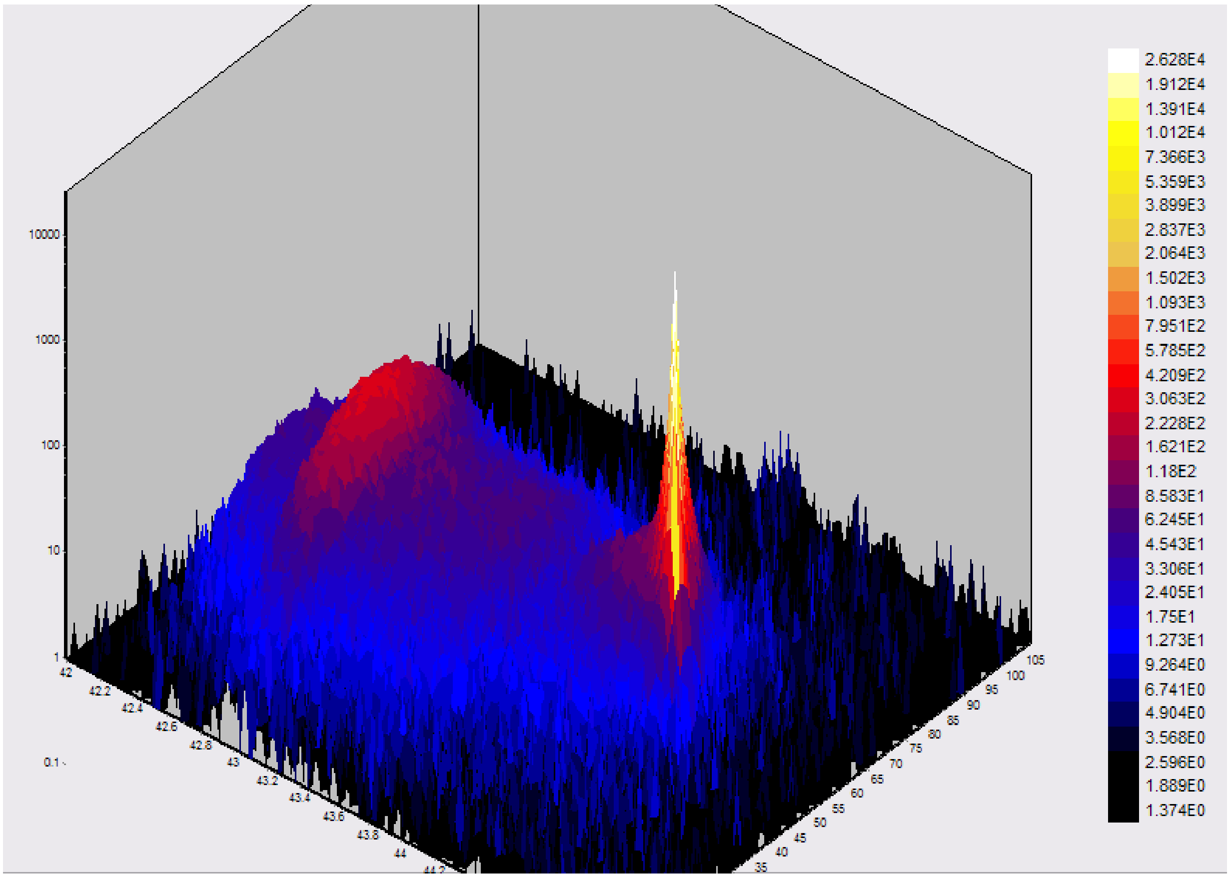

Fig. 8 X-ray RSM of the mHEMT epi material.

七、參考文獻：

[1] S. Bollaert, Y. Cordier, M. Zaknoune, T. Parenty, H. Happy, S. Lepilliet, and A. Cappy, Electronics Lett. 38 (2002) 389.

[2] C. S. Whelan, P. F. marsh, W. E. Hoke, R. A. McTaggart, P. S. Lyman, P. J. Lemonias, S. M. Lardizabal, R. E. Leoni III, S. J. Lichwala, and T. E. Kazior, IEEE J. Solid-State Circuits 35 (2000) 1307.

[3] C. S. Whelan, W. E. Hoke, R. A. McTaggart, S. M. Lardizabal, P. S. Lyman, P. F. Marsh, and T. E. Kazior, IEEE Electron Device Lett. 21 (2000) 5.

[4] C. K. Lin, J. C. Wu, W. K. Wang, Y. J. Chan, J. S. Wu, Y. C. Pan, C. C. Tsai, and J. T. Lai, IEEE Trans. Electron Devices 51 (2004) 1214.

[5] W. C. Hsu, Y. J. Chen, C. S. Lee, T. B. Wang, J. C. Huang, D. H. Huang, K. H. Su, Y. S. Lin, and C. L. Wu, IEEE Trans. Electron Devices 52 (2005) 1079.

[6] D. C. Dumka, H. Q. Tserng, M. Y. Kao, E. A. Beam, and P. Saunier, IEEE Electron Device Lett. 24 (2003) 135.

八、成果自評：

We have performed about 85% of the project progress that we planned in the beginng. The items we have finished include:

-- Calibration of the MBE growth parameters.
-- Optimizing the MBL growth conditons.
-- mHEMT epi wafer growth.
-- Characterization of epi wafers and devices.
-- Low pinch-off leakage mHEMT fabrication.

However, some hardware troubles in the optical instrument system delayed the measurement of the opto-detection response of the mHEMT devices, making us unable to complete this item before the deadline of the tight project schedule. We will continue the optical measurement in the on-going NSC project that has already been granted.