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SWIR InGaAs PhotoFETs on Half-inch Si Wafer Using Layer Transfer Technology

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Abstract

Fabrication and optical characteristics of InGaAs photoFETs transferred to a half-inch Si wafer using layer transfer technology have been demonstrated. The high film quality of transferred InGaAs layer on Si was verified by Raman spectroscopy and TEM. The optical performance of InGaAs photoFETs on Si, operating in shortwave infrared (SWIR) region was also investigated.

1. Introduction

The InGaAs field-effect phototransistors (photoFETs) are potentially the most promising candidate for ultrafast photodetectors for shortwave infrared (SWIR) region in optical communication and interconnect applications as well as SWIR imaging. They have many advantages over p-i-n structures, such as low parasitic capacitance, wide bandwidth, planar structure, and compatible fabrication with conventional FETs. Generally, InGaAs photoFETs require hybrid integration with the readout circuit, which is typically fabricated using Si. Therefore, heterogeneous integration of InGaAs photoFETs on Si substrates with cost-effective process would be a key technology to extend the usability of InGaAs photoFETs [1]. In this work, InGaAs photoFETs on Si wafer by layer transfer technology were demonstrated. Furthermore, electrical and optical performances of the fabricated InGaAs photoFETs with back gate structure were characterized.

2. General Instructions

Fig. 1 shows the process flow of InGaAs/InP hetero-structures on the half-inch Si wafer by layer transfer technology developed in this study. As a donor wafer, we prepared the epitaxially grown lattice-matched $In_{0.53}Ga_{0.47}As/InP/In_{0.53}Ga_{0.47}As/InP$ substrate structure by MOCVD. After ALD-Al_2O_3 deposition on the top, the donor wafer was bonded with the half-inch Si wafer, which is a Minimal Fab standard wafer [2]. Then, Al_2O_3, InGaAs, InP, and InGaAs layers were wet etched subsequently to expose InP substrate. Here Si wafer act as an etching mask. This structure was molded by a photoresist with a dicing plastic sheet for covering front side. Finally, InP substrate was etched away from back side to obtain InGaAs/InP/InGaAs/Al_2O_3 on half-inch Si wafer (Type I). By etching InGaAs and InP layers consequently, we attained Type II and III structures.

InGaAs photoFETs were fabricated with Type II structure (Fig. 2 (a)). After the mesa isolation, InP layer in contact area was etched to ensure contact to InGaAs channel. Au/Pt/Ti was deposited as contact metal and formed by lift-off process, followed by rapid thermal annealing (RTA) at 350 °C. The back-gate bias applied on Si wafer through Al_2O_3 dielectric enables us to fulfill the front side illumination. Fabricated photoFET array with the half-inch Si wafer was also presented in Fig. 2 (b). The optical measurement was performed at room temperature on a probe station through an optical fiber (spot diameter of 193 μm as shown in Fig. 2 (c)). The output and transfer characteristics of InGaAs photoFETs with a gate length and width of 100 μm and 100 μm were first measured without any illumination and then under illumination at different SWIR wavelength and excitation power.

3. Results and Discussion

Transferred InGaAs/InP hetero-structures were evaluated by Raman spectra and TEM. Fig. 3 shows HAADF-STEM image and EDX elemental mappings of Type I structure, which indicates successful transfer of InGaAs/InP/InGaAs/Al_2O_3 herero-structure on Si wafer. The thicknesses of the InGaAs, InP, InGaAs, and Al_2O_3 layers were about 100, 50, 50, and 10 nm, respectively and each interface was found to be very clear and sharp without any identifiable defects. Fig. 4 show Raman spectroscopy of InGaAs layer on Si wafer after layer transfer (Type III) and InGaAs/InP wafer. The peaks of InAs-like and GaAs-like LO modes were observed in both samples. However, only the transferred sample displays Si phonon peak because the penetration depth of excitation wavelength is larger than InGaAs layer thickness (50 nm). The transferred sample shows almost the same Raman shift compared with InGaAs/InP substrate, indicating that there is no perceptible strain in the transferred layer.

Fig. 5 show I_d-V_g characteristics at drain voltage (V_d) of 50 mV under dark and the changes in the output drain current under SWIR illumination with different incident power (P_{in}) for excitation wavelength of 1550 and 1710 nm. In $V_g > V_{th}$, we clearly observed higher photoresponse at 1550 nm than that at 1710 nm which is closer to cut-off wavelength. The photocurrent, $I_{ph}=I_{illumination}-I_{dark}$, are then extracted at different P_{in} and V_g and plotted in Fig. 6. Increasing V_g lowers the barriers at the contacts, resulting in more efficient extraction and increased photoresponse. Fig. 7 show the responsivity, $R=I_{ph}/P_{in}$, of InGaAs photoFETs at V_g = 0 and 1 V. Unlike I_{ph}, R increases with decreasing P_{in} as photo carrier life time could be longer in a photoconductor under lower excitation power. Field effect also enhanced R due to the reduction of carrier transit time with increased gate bias. Despite low V_d and large gate length, high responsivity of ~3A/W was achieved, showing suitability of photoFETs utilizing layer transfer technology as the front illuminated SWIR detector.

3. Conclusions

The first InGaAs photoFETs transferred onto a half-inch Si wafer were successfully demonstrated. The good quality of the transferred film was confirmed by Raman and TEM observations. The measured optical gains of the devices were higher than ~3 A/W in the investigated range of bias, that is promising for high performance InGaAs photoFETs on Si wafer.

Acknowledgements

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References

[1] T. Maeda et al., *Microelectron. Eng.* **109**, 133 (2013).

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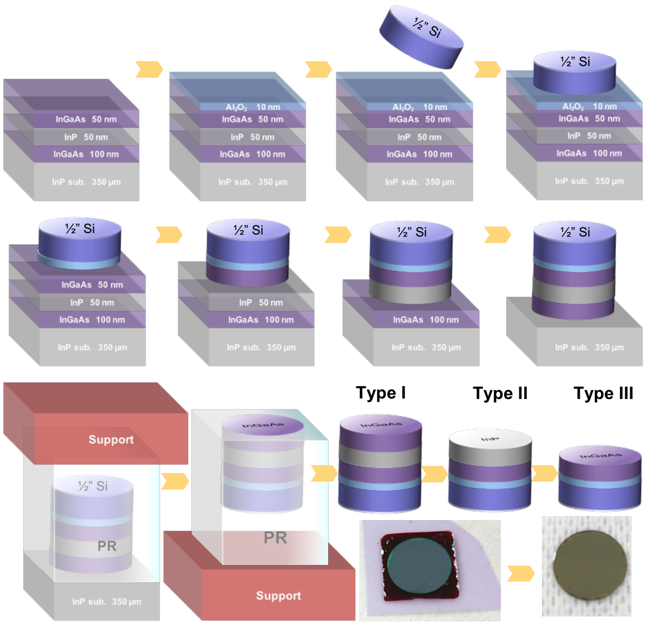

Fig. 1 Process flow of InGaAs/InP hetero-structures on the half-inch Si wafer by layer transfer technology and their photo images.

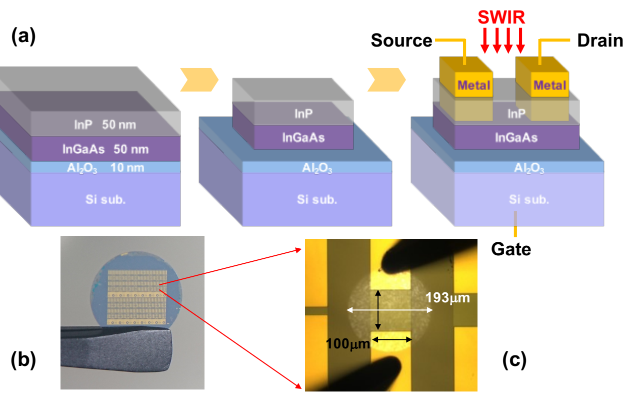

Fig. 2 (a) Process flow of InGaAs photoFETs. (b) Photo images of InGaAs photoFET array on the half-inch Si wafer and (c) InGaAs photoFET under SWIR illumination.

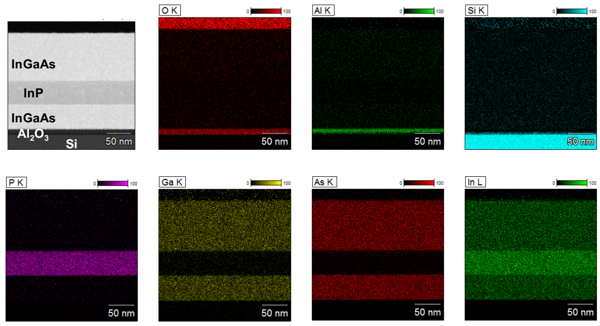

Fig.3. Cross-sectional HAADF-STEM with the corresponding EDX maps of O, Al, Si, P, Ga, As, and In taken from Type I.

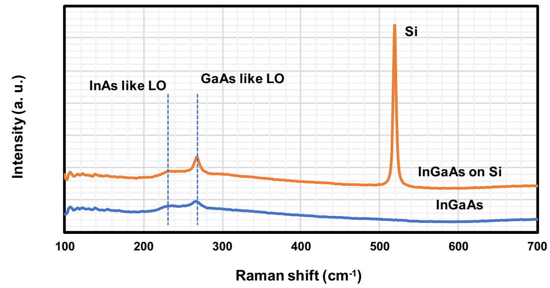

Fig. 4. Comparison of Raman spectra of the InGaAs layer on Si wafer after layer transfer (Type III) and InGaAs/InP substrate.

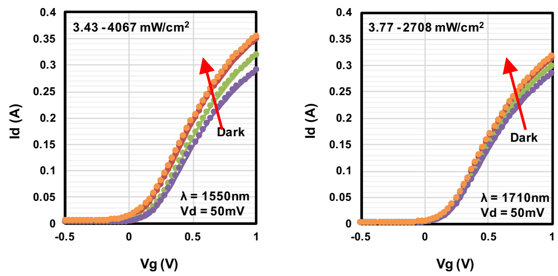

Fig. 5. I_d-V_g characteristics of InGaAs photoFETs under dark and illumination with different incident power at excitation wavelength of 1550nm and 1710nm.

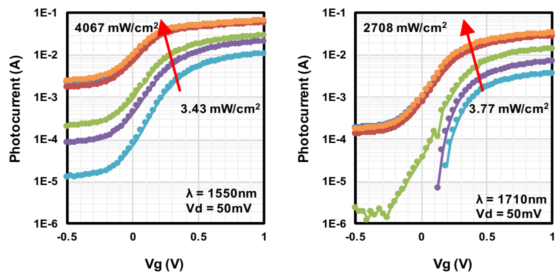

Fig. 6. Photocurrent (I_{ph}) of InGaAs photoFETs with different incident power.

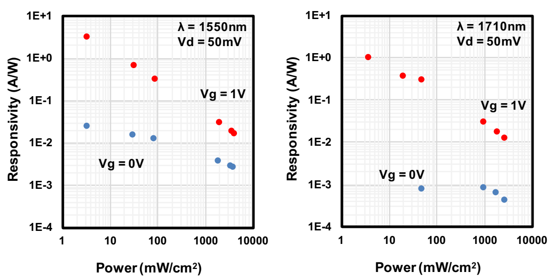

Fig. 7. Incident power dependence of Responsivity (R) of InGaAs photoFETs at V_g = 0 and 1 V for 1550nm and 1710nm.