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# GeSn Based Near and Mid Infrared Heterostructure Detectors

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Group-IV photonics on Si platform is an important and emerging area that has attracted much attention from both academia and industry, driven by the need for the integration of photonic devices with Si electronics to enhance the performance of optoelectronic systems. Two key results are summarized in this report. As a result, practical devices are possible. These are: (a) direct bandgap group IV materials of GeSn with lowest defect density and highest Sn content for the material, (b) Evaluation of GeSn-based photodetector and a comparison with commercial bulk Ge photodetector at 1550 nm. These results provide a direct impact to the all group IV photonic as well as paving the way to the monolithic integration of optic and electronic devices in a single chip which will be eventually realized in the Si-based foundry on optoelectronic chip.

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**Abstract:**

Group-IV photonics on Si platform is an important and emerging area that has attracted much attention from both academia and industry, driven by the need for the integration of photonic devices with Si electronics to enhance the performance of optoelectronic systems. Here, I like to summarize our two results that is recognized by the community. As a result of these works, the practical devices is under-way. These are: (a) direct bandgap group IV materials of GeSn with lowest defect density and highest Sn content for the material, (b) Evaluation of GeSn-based photodetector and a comparison with commercial bulk Ge photodetector at 1550 nm. These results provide a direct impact to the all group IV photonic as well as paving the way to the monolithic integration of optic and electronic devices in a single chip which will be eventually realized in the Si-based foundry on optoelectronic chip.

This report is divided into the following sections:

(a) Direct bandgap group IV material with lowest defect density and highest Sn content reported in the literature

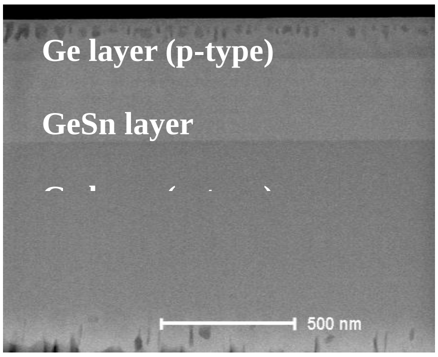
(b) Evaluation of GeSn-based photodetector and a comparison with commercial bulk Ge photodetector at 1550 nm

(c) Publications as a result of this program (2016-2017)

(a) Direct bandgap group IV material with lowest defect density and highest Sn content reported in the literature.

Regarding material growth, there are quite a few issues such as the low melting of Sn etc.. Several techniques are developed to overcome these difficulties and our results show that: (a) GeSn film with lowest defect density and highest Sn content reported in the literatures, and (b) the quality of the film has already reach the standard used in the foundry as that of SiGe/Si which is used for the 45 nm node in strained central processing unit (CPU).

The GeSn film is grown on two type of wafer Si and Ge. Here, the film grown on Ge (001) n type wafer is outlined. P-i-N diode structure consists of Ge/GeSn/Ge layers was grown on a Ge (001) wafer. A transmission electron microscopy TEM image of the sample is plotted in Figure 1(a), and a high-resolution X-ray trace around the energy range of the active layer is shown in Figure 1(b). The full width at half maximum (FWHM) of the GeSn layer was 85″. This gave a defect density of $5 \times 10^{6}$ $cm^{-2}$ as calculated with the Hirsch model. This value is an overestimate because the measured signal included not only the signals from the GeSn epilayer but also the background signals of the equipment setup and the broadening caused by the finite thickness of the GeSn layer. Measurement of the wafer gave an HWHM of 30″. Therefore, a lower defect density was expected for the GeSn layer. Without considering the background signal, compared with our previous work and work reported in the literature, the defect demsity is still the lowest reported in the literature.



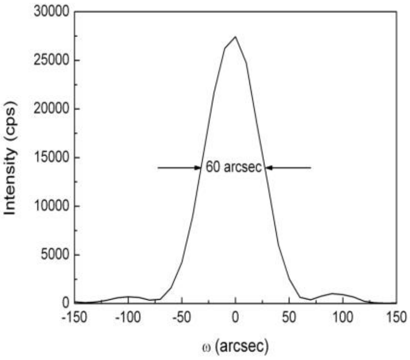


Figure 1. Left: (a) Structural TEM image of sample. Right: Spectrum of X-ray (004) ω-2θ measurements of the sample.

(b) Evaluation of GeSn-based photodetector and a comparison with commercial bulk Ge photodetector at 1550 nm

Photodetector (PD) fabricated from these high quality films was made. GeSn-based PD with best clarity at the energy range from near- to mid-infrared has been achieved. The next stage involves determining whether the performance of Sn-containing photonic devices meets the requirements for commercial application. In this sub-program, the performance of GeSn-based photodetector is evaluated. The structure and usage of Si-based foundry processing technology were examined. The results of the evaluation indicated a performance comparable to that of a currently marketed Ge bulk photodetector. There are various parameters which characterises a photodetector and its applications in different fields. Here, a few key parameters of spectral response, responsivity, dark current, quantum efficiency, specific detectivity (noise equivalent power) are discussed. Fabrication based on these proposed techniques is under investigation,

Figure 2(a) shows the spectral responsivity of the diode under illumination without applied voltage of our result on P-i-N photodiode consist of Ge/GeSn$_{3.4\,\%}$/Ge with a thickness of 160/240/160 nm The responsivity (R) gradually decreased as the wavelength of incident light increased and dropped rapidly as the wavelength of incident light approached the strain-dependent bandgap of the GeSn alloy. When voltage was applied under a reverse bias across the P- and N-type contacts, R at 1550 nm increased rapidly, then gradually saturated as the bias was further increased, reaching a maximum value of about 0.35 A/W. This is plotted in Figure 2(b). Based on R and the dark current of the detector discussed above, the other key factor for photodetectors—the detecting ability—can be determined. When normalized to the noise current, the specific detectivity ($\mathrm{D}^{*}$) is $\mathrm{R} * \Delta\mathrm{f} * \mathrm{A}/\mathrm{I}_{\mathrm{noise}}$, where Δf is the signal bandwidth, A is the area of the photodiode, and $\mathrm{I_{noise}}$ is the noise current found by the dark current. The result is plotted as a dashed line in Figure 2(b). $\mathrm{D^*}$ decreased with increasing bias; this was mainly caused by the increase in the dark current from $2 \times 10^9$ to $4 \times 10^9$ cm $\mathrm{Hz^{1/2}\,W^{-1}}$. These values for R and $\mathrm{D^*}$ are reasonable for a GeSn-based thin-film PIN photodiode. Compared with the biased bulk Ge photodiode available on the market, R is about half as much, and $\mathrm{D^*}$ is about an order of magnitude smaller (compared to Thorlab's item number: DET50B with an area of 19.6 $\mathrm{mm^2}$ operated at 5 Volts, whose R = 0.8 A/W and D* = $4.9 \times 10^{10}$ cm $\mathrm{Hz^{1/2}\,W^{-1}}$).

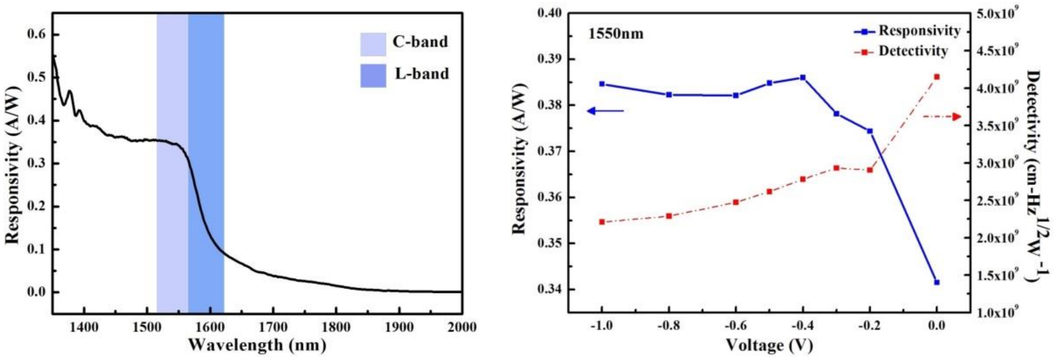


Figure 2: Left plot: Spectral responsivity of the diode under illumination without applied voltage. The result shows that, it cover both C- and L-band. Right plot: Spectral responsivity and specific detectivity of the diode under applied voltage with reverse bias.

To increase this performance, the structure and usage of Si-based foundry processing technology were examined. Several well-established technologies can also be employed. For instance, the dopant density in the P- and N-type layers can be further increased to enhance the electric field and thus to enhance R. Among these approaches, the use of an anti-reflection coating layer like that used in commercial Ge photodiodes was examined because the coating layer not only protects the diode but also increases the throughput of the incident light. For the sample used in this investigation, with normally incident light, the reflections at the air/SiO and SiO/Ge interfaces were 4 % and 12.6 %, respectively, and the absorption in the P-type Ge layer was 0.6 %. This indicates a large loss of 17.2 % for the incident light power before it reached the active GeSn layer. To reduce that loss, the commercial product uses a quarter-wave anti-reflection coating, which produces destructive interference in the layer and thus increases R. Using that AR here, we expect a 17 % improvement in our R. With regard to the detectivity of the material, a very low defect density was observed in the GeSn epilayer. Therefore, another factor was considered: the surface leakage current. Recent studies have employed a surface passivation technique to suppress the surface leakage current. The technique deposits a thin layer between the GeSn sidewall and the insulating layer in order to repair defects at the GeSn sidewall surface due to processing and to improve chemical bonding. Two types of thin layers were considered: Si and $GeO_2$. In the previous investigation, it shows that when $GeO_2$ was used on an $N^+$-Ge/$P^+$-Ge photodiode grown by thermal oxidation, the surface leakage current was reduced by an order of magnitude. Applying to our sample, the noise current was then reduced from $2 \times 10^{-11}$ A to $2 \times 10^{-12}$ A, therefore the specific detectivity increased according to the measured responsivity from $3 \times 10^9$ to $3 \times 10^{10}$ cm $Hz^{1/2}$ $W^{-1}$. This is comparable to the performance of the aforementioned biased commercial Ge photodetector (the specification is listed in the right plot. Thorlab‘s item number: DET50B) and the extended InGaAs photodetector at $3 \times 10^{10}$ cm $Hz^{1/2}$ $W^{-1}$.

(c) Publications as a result of this program (2016-2017).

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