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Monolithic Integration of InSb Photodetector on Silicon for Mid-Infrared Silicon Photonics

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ABSTRACT

The InSb photodetector on a Si substrate acts a signal receiver for the mid-infrared silicon photonics application to overcome the limitation of group IV semiconductors. In this paper, we demonstrated an InSb p-i-n photodetector with an InAlSb barrier layer grown on (100) silicon substrates via a GaAs/Ge buffer by molecular beam epitaxy. The lattice mismatch between InSb and GaAs was accommodated by an interfacial misfit (IMF) array. The 50% cutoff detectable wavelength of this detector increased from 5.7 μm at 80 K to 6.3 μm at 200 K. An 80 K detectivity of $8.8 \times 10^9 \text{ cmHz}^{1/2}\text{W}^{-1}$ at 5.3 μm was achieved with a quantum efficiency of 16.3%. The dark current generating mechanism of this detector is both generation-recombination and surface leakage above 140 K, while it is only surface leakage from 120 K to 40 K.

KEYWORDS: monolithic integration, mid-infrared photodetector, III–V on silicon, molecular beam epitaxy, InSb

In the past decades, Si photonics has received great attention due to its potential in the on-chip optical interconnection to overcome the limitation of electrical interconnection¹. Extending the recent operating wavelength of Si photonics from near-infrared (NIR) to mid-infrared (MIR) can provide more channels for communication in on-chip optical interconnection. Moreover, MIR Si photonics is a fundamental platform for the emerging lab-on-chip technology because the MIR spectrum (3-8 μm) includes the fingerprint information of particular chemical molecules and functional groups²⁻⁴. Si, other IV group semiconductors, and their alloys are transparent in the range of MIR, which allows MIR light to transmit over a Si platform with minimal loss³. Recently, MIR Si photonics devices, such as SOI waveguide⁵, silicon-on-BTO waveguide², 4.8 μm laser on Si⁶, and Si-on-sapphire ring resonators⁷ have been demonstrated. Applications such as label-free glucose sensing⁸ and spectrometers operating around 3.8 μm ⁹ have also been demonstrated using MIR Si photonics devices.

The photodetector is an essential component of the MIR Si photonics system. Monolithic integration of MIR devices on Si could be implemented using the hetero-epitaxial growth of MIR material on a Si substrate, which does not require a complicated wafer bonding process. In the hetero-epitaxy process, a large lattice mismatch between MIR material and Si substrate results in a high threading dislocation density¹⁰. Group IV semiconductors such as GeSn and Ge/SiGe have been investigated for MIR applications. A strained or low defect fully relaxed GeSn and Ge/SiGe type II superlattice can be grown on Si because of their small lattice mismatch with Si substrate¹¹⁻¹³. However, the quantum efficiency of the Ge/SiGe type II superlattice is very low (below 1%)¹⁴ and the longest cutoff wavelength achieved in the GeSn photodetector is about 3 μm ¹⁵. On the other hand, InSb is one of the materials for the commercial MIR photodetector due to its 300 K bandgap of 0.17 eV. An InSb p-i-n photodetector could achieve a cutoff detection wavelength of 5.5 μm and a detectivity above $10^{11} \text{ cmHz}^{1/2}\text{W}^{-1}$ at 5.3 μm at 77 K. Detection spectra between the 3-5.5 μm region includes the absorption bands of some important molecules and functional groups, such as a hydroxyl ($-\text{OH}$) stretch at 2.73-3.10 μm , an alkyl ($\text{C}-\text{H}$) stretch at 3.3-3.6 μm , a CO_2 stretch at 4.3 μm and a N_2O stretch at 4.5 μm ^{8, 16}. For the application in the high frequency region, the InSb detector on GaAs achieved a 300K cutoff frequency of 8.5 GHz at 1.55 μm ¹⁷. As another widely used material for mid-infrared detector, HgCdTe detector on GaAs achieved a 212 K cutoff frequency of around 0.4

GHz at $10\text{ }\mu\text{m}^{18}$. Structure Optimization of p-i-n photodetector could increase the cutoff frequency¹⁹. Due to high mobility and short lifetime of carriers, 2D materials, such as black phosphorous, could achieve high cutoff frequency²⁰. Black phosphorus phototransistor has demonstrated a 300 K cutoff frequency of 2.2 kHz at $3.39\text{ }\mu\text{m}^{21}$.

The growth and fabrication of an InSb p-i-n photodetector on a InSb native substrate is a mature process²². However, the hetero-epitaxy of InSb on Si is still challenging because InSb and Si have a dissimilar crystal structure (polar vs. non-polar) and there is a large lattice mismatch (19.3 %) between them. Moreover, direct depositing In and Sb atoms does not form a continuous InSb layer on the (100) Si surface due to the preference of Sb atoms to bond with Si atoms instead of In atoms²³. Therefore, an intermediate buffer is needed for the growth of InSb on Si. GaAs and Ge have been used as a buffer to grow InSb on Si²⁴⁻²⁵. InSb p-i-n detector has been grown on the GaAs-coated Si substrate²⁶⁻²⁷ and E. Michel *et al.* developed the InSb p-i-n with $6\text{ }\mu\text{m}$ i-layer on GaAs-coated Si where its highest detectivity was estimated to be $2.8\times 10^{10}\text{ cmHz}^{1/2}\text{W}^{-1}$ at 77 K²⁶. However, the large lattice mismatch between InSb and the intermediate GaAs or Ge (14.6%) results in a high threading dislocation density. Therefore, a dislocation reduction technique is required to reduce the defect density.

In this work, InSb photodetectors were grown on a 6° offcut (100) Si substrate via the GaAs/Ge buffer as shown in Figure 1(a). The Ge buffer was grown on Si substrates by a chemical vapor deposition (CVD). The GaAs buffer and InSb device structure were grown by a solid-state molecular beam epitaxy (MBE) system. The 6° offcut Si substrate and migration-enhanced epitaxy (MEE) growth method were employed to minimize the anti-phase boundary (APB), which resulted from the misalignment between GaAs (polar structure) and Ge (non-polar structure). An interfacial misfit (IMF) array consisting of uniformly distributed 90° misfit dislocations was intentionally formed at the InSb/GaAs interface to accommodate the 14.6% lattice mismatch²⁸. Transmission electron microscopy (TEM) observation confirmed a low defect InSb layer. An electron barrier layer ($\text{In}_{0.82}\text{Al}_{0.18}\text{Sb}$) was inserted into the absorption layer of the InSb photodetector to suppress the dark current. The barrier allowed only one type of carrier (either electron or hole) to flow through the device²⁹. In this study, the barrier layer was placed in the middle of i-layer. This placement was aimed to suppress the dark current generated in the p-type region, PN junction and the i-layer below it. Its

effect on the dark current suppression was better compared to placing the barrier layer in the p-type region²⁹.

The application of the barrier layer on the InAs and InSb detector effectively decreased their dark currents and increased their operating temperatures²⁹⁻³⁰. Spectra responses up to a wavelength of 5.5 μm was obtained at 80 K. A responsivity of 0.7 A/W and a detectivity of $8.8 \times 10^9 \text{ cmHz}^{1/2}\text{W}^{-1}$ were achieved at 5.3 μm at 80 K.

■ RESULTS AND DISCUSSION

Crystal Structure. Figure 1(b) shows the optical microscopic images of the InSb photodetectors. The mesa of the detectors included a square contact area and a circular exposed area. A single ring-shaped electrode was placed around the mesa to collect photo-generated carriers. The detectors shown in Figure 1(b) have mesa areas of 0.0145 mm^2 , 0.0216 mm^2 , 0.0787 mm^2 , and 0.172 mm^2 (from right to left). The larger detector (not shown) has a mesa area of 0.388 mm^2 . Figure 1(c) shows a 10 $\mu\text{m} \times 10 \mu\text{m}$ atomic force microscope (AFM) image that demonstrates the surface of the InSb layer on Si via the Ge/GaAs buffer. The roughness (r.m.s.) of the surface was 1.6 nm, and no obvious defect or step was observed in the AFM image. The low surface roughness minimized diffused light reflection at the surface of the photodetector, which could deteriorate the performance of the detector.

Figure 1. The schematic of InSb photodetector on Si and material characterization of the heteroepitaxial structure. (a) The InSb p-i-n photodetector with an $\text{In}_{0.82}\text{Al}_{0.18}\text{Sb}$ barrier layer grown on a 6° offcut Si substrate via the GaAs/Ge buffer. (b) Optical microscopic image of the fabricated InSb photodetector. (c) A 10 $\mu\text{m} \times 10 \mu\text{m}$ AFM image of InSb layer on Si. (d) X-ray (115) reciprocal space map (RSM) of InSb layer on Si. (e) TEM image for GaAs layer grown on the Ge-on-Si substrate. (f) TEM image of InSb layer grown on GaAs where a highly periodic interfacial misfit (IMF) array locating at the InSb/GaAs interface. (g) High resolution TEM image of the IMF array shown in (f) and the separations (3.2 nm) of misfit dislocations are indicated.

Figure 1(d) shows an x-ray reciprocal space map (RSM) from an asymmetric (115) lattice plane. The lattice constant of all layers in a parallel direction can be calculated

using Q_x . The GaAs peak overlapped with the Ge peak, which indicates a minimal lattice mismatch between GaAs and Ge. The diagonal and vertical dashed lines in Fig. 1(d) indicate the reciprocal lattice for fully relaxed and fully strained layers, respectively. The InSb peak is located along the diagonal dashed line: indicating a fully relaxed InSb layer. The in-plane lattice constant of the InSb layer was measured to be 6.471 Å, which implied a 99.4% of relaxation in the InSb layer. Above the InSb peak, a weak signal peak was observed, which could be attributed to the InAlSb layer. The signal peak of the InAlSb layer has an identical Q_x value with the InSb peaks, implying an identical in-plane lattice constant in these two layers. The composition of the InAsSb were determined to be $\text{In}_{0.82}\text{Al}_{0.18}\text{Sb}$ using (004) ω - 2θ scan (see Section II in the Supporting Information for details).

Microstructures of the InSb layer and GaAs/Ge buffer were observed using cross-sectional TEM. Figure 1(e) shows the GaAs and Ge layers on Si. Even though the lattice mismatch between Ge and Si was about 4.18%, only a few defects are observed at the Ge/Si interface. No threading dislocation is observed at the interface due to the optimal growth process¹¹. Some black dots were observed at the Ge/GaAs interface. Considering the negligible lattice mismatch between GaAs and Ge, these dots could be attributed to surface contamination rather than to dislocations. The Ge/Si substrates were exposed to the atmosphere during the transfer from the CVD chamber to the MBE chamber, which led to surface contamination. Because the Ge-on-Si substrate was 6° offcut and thermal annealing was applied on the substrate before the growth of GaAs to form double-atomic-height steps on the Ge surface, no APB is observed in the GaAs layer³¹.

Figure 1(f) shows the InSb/GaAs interface. A high density of black dots is observed distributed uniformly along the interface. No threading dislocation is observed to arise from the InSb/GaAs interface. Figure 1(g) is a high resolution TEM image, which shows these dots are periodically distributed 90° misfit dislocations and the separation between them is 3.2 nm (see Section III in the Supporting Information for details about the type of dislocation and microstructure at the InSb/GaAs interface). These results

were consistent with the previous studies^{28, 32} about InSb grown on GaAs using an IMF array. The lattice mismatch between InSb and GaAs was accommodated by a highly periodical distribution of 90° interfacial misfit dislocations. This structural characterization suggested that the entire hetero-epitaxial structure agreed well with the design as described in Fig. 1(a). A low-defect density InSb layer on Si was grown for further development of the InSb photodetector.

Electrical Property. Figure 2(a) shows the dark current density (J_{dark}) vs. bias voltage at different temperatures from 5 K to 300 K for the detector with a mesa area of 0.0787 mm². The mesa area includes both the circular area for light sensing and the square area, where the n+ contact located on as shown in Figure 1(b). The dark current density increased with increasing temperature. The dark current density in the reverse bias region increased by a factor of 9 from 5 K to 300 K. At reverse bias voltage ($V_{\text{bias}} = -50$ mV), the 300 K J_{dark} was 3.4 A/cm². The 80 K J_{dark} at -50 mV was 0.085 A/cm², which was comparable to the reported InSb photodetector on GaAs via a 100 nm GaSb buffer with the J_{dark} of 0.11 A/cm²³⁴. However, it was much higher than the J_{dark} ($\sim 10^{-7}$ A/cm²) of the InSb photodetector on InSb³⁵.

Figure 2. (a) Bias voltage dependent dark current density (J_{dark}) at different temperatures for the detector with a mesa area of 0.0787 mm^2 . (b) 80 K dark current density for the photodetector with and without the $\text{In}_{0.82}\text{Al}_{0.18}\text{Sb}$ barrier layer. (c) and (d) Plot of $\ln(J_{\text{dark}})$ vs. $1/kT$ for the device presented in (a). The solid lines are the Arrhenius fitting using eq 1 from 60 K to 300 K (c) and from 5 K to 100 K (d), respectively. (e) and (f) The relationship between the perimeter to area (P/A) ratio and $1/R_0A$ for photodetectors with different sizes at 80 K(e) and 200 K(f). The solid lines are the fitting using eq 2 and the fitted results are shown in (e) and (f), respectively.

The dark current can be mainly attributed to threading dislocations in the InSb layer because the effect of threading dislocations on the dark current is remarkable when its density is higher than 10^6 cm^{-2} ³⁶. The threading dislocation density in a $0.7 \text{ }\mu\text{m}$ InSb layer grown on GaAs using IMF array was reported to be $1.38 \times 10^8 \text{ cm}^{-2}$ ²⁸. To identify

the effect of the $\text{In}_{0.82}\text{Al}_{0.18}\text{Sb}$ electron barrier layer on the dark current, a sample without this barrier layer was prepared. The growth and fabrication process of this control device (without the barrier layer) was identical to that for the device with the barrier layer. Figure 2(b) shows the comparison of the 80 K $J_{\text{dark}}-V_{\text{bias}}$ curves of the InSb photodetector with and without the barrier layer (the band diagrams of InSb photodetector with and without the barrier layer are shown in Figure S4 in the Supporting Information). At $V_{\text{bias}}=-0.5\text{V}$, the J_{dark} of the detector with the barrier layer is 5.28 A/cm^2 , while that of the detector without the barrier layer is 12.81 A/cm^2 . The 80 K zero bias resistance (R_0) of the detectors with and without the barrier layer is $905\ \Omega$ and $247\ \Omega$, respectively. Ueno, et al. utilized a similar barrier layer in the InSb detector grown on GaAs and increased the R_0 by 70% at 300 K²⁸.

To investigate the dark current generating mechanism in this device, the temperature dependent dark current density (J_{dark}) under $V_{\text{bias}}=-50\text{ mV}$ was fitted using the Arrhenius plot, which is expressed as

$$J_{\text{dark}} = J_0 \exp\left(-\frac{E_a}{k_B T}\right) \quad (1)$$

where J_0 is the pre-exponential factor, E_a is the activation energy, k_B is the Boltzmann constant, and T is temperature. The fitted results are shown in Figure 2(b) and (c). Based on different activation energies, the temperature dependent J_{dark} at $V_{\text{bias}}=-50\text{ mV}$ was divided into three regions. In Region I from 300 K to 140 K, the activation energy was $61\pm0.7\text{ meV}$, which was about one-third of the bandgap of intrinsic InSb (0.17 eV at 300 K). Within this temperature range, the activation energy was significantly smaller compared to the bandgap of InSb. Normally, dark current generation is attributed to the generation-recombination (G-R) mechanism where the thermally generated carriers are excited from the valence band to the conduction band via the defects existing between these two bands³⁷. However, the G-R mechanism has an activation energy that is half of the semiconductor bandgap energy. Therefore, other factors should be considered in the dark current mechanism, such as surface leakage³⁸.

In Region II from 120 K to 40 K, the activation energy decreased to about 3.0 meV. A previous study on narrow bandgap semiconductor-based photodetectors suggested this small activation energy was attributed to surface leakage³⁹. The effect of surface leakage will be investigated later by utilizing detectors with different sizes. The activation energy in Region III (below 40 K) only involved two data points measured at 20 K and 5 K, respectively. Although the activation energy in this region could not be estimated due to limited data, the dark current density was weak temperature dependent, which indicated a different dark current mechanism from Region I and II.

A previous study on the GeSn photodetector suggested that the dark current density at an ultra-low temperature was affected by carrier freeze out⁴⁰. However, the carrier freeze out was strongly depended on temperature⁴¹, which disagreed with the result in Region III. For a narrow bandgap semiconductor-based photodetector, the effect of the carrier tunneling mechanism could not be ignored. Under reverse bias, carriers may tunnel through the depletion region (PN-junction) into the other side of the junction to form a tunneling dark current. The tunneling dark current was nearly temperature independent and strongly depended on reverse bias⁴². As shown in Figure 2(a), the 5 K and 40 K $J_{\text{dark}}-V_{\text{bias}}$ curves show the strong reverse bias dependent J_{dark} . Moreover, a study on the HgCdTe photovoltaic photodetector suggested domination of the tunneling mechanism in the dark current mechanism at a low temperature⁴³. Therefore, the dark current mechanism in Region III could be the tunneling mechanism.

The surface leakage mechanism could be responsible for the dark current generated in Regions I and II, as mentioned earlier. To characterize the surface leakage current, the relationship between the zero bias resistance-area product (R_0A) and the perimeter-to-area (P/A) ratio of the photodetector was measured. Figure 2(e) and (f) shows the inverse of R_0A ($[R_0A]^{-1}$) as a function of P/A at 80 K and 200 K. The R_0 data is obtained through measuring the $J_{\text{dark}}-V_{\text{bias}}$ curves of the detector with different mesa sizes. At both temperatures, the $[R_0A]^{-1}$ of the devices increased with the increasing P/A , which indicated the influence of surface leakage. However, the device with the largest area ($P/A=40.8 \text{ cm}^{-1}$) did not agree with the linear relationship between P/A and $[R_0A]^{-1}$.

An explanation for this observation is the current localization effect for the detector with a large exposed area³³. As shown in Figure 1(b), the top electrode of the detector is ring-shaped on the mesa. Thermally generated carriers at the center of the mesa area were not collected by the electrode. Consequently, the measured dark current did not cover all thermally generated carriers. A lower measured J_{dark} results in a lower $[R_0A]^{-1}$. Therefore, the $[R_0A]^{-1}$ scaling was saturated for the detector with a large exposed area. Notably, the current localization effect also suppressed the collection of photon-generated carriers when the detector was exposed to light³³, and this effect will be discussed in Figure 3.

To investigate the contributions of surface leakage and bulk to R_0A , the $[R_0A]^{-1}$ of the other four devices with smaller mesa areas were fitted using the formula as

$$\frac{1}{R_0A} = \frac{1}{R_0A_{\text{bulk}}} + \frac{1}{r_{\text{surface}}} \frac{P}{A} \quad (2)$$

where R_0A_{bulk} is the bulk contribution, r_{surface} is the surface resistivity, and P/A is the perimeter-to-area ratio of the detector. The fitted results (black solid lines and parameters) at 80 K and 200 K are shown in Figure 2(e) and (f), respectively. Obviously, the slope of the line is $1/r_{\text{surface}}$ and the intercept is $1/R_0A_{\text{bulk}}$. At 80 K, the surface resistivity, r_{surface} , was calculated to be 88.26 Ωcm and the R_0A_{bulk} was 93.28 Ωcm^2 . At 200 K, the r_{surface} was 10.89 Ωcm and the R_0A_{bulk} was 0.088 Ωcm^2 . Therefore, the contribution of the surface leakage current to the dark current was remarkable at 80 K. The surface leakage current also played a non-negligible part in the dark current at 200 K. This result agreed with the earlier suggestion that the dark current mechanism from 120 K and 40 K was surface leakage. Moreover, the effect of surface leakage on R_0A also explained that the activation energy of the temperature dependent J_{dark} above 120 K, which was about one-third of the InSb bandgap energy. The dark current generating mechanism above 120K involved both the G-R mechanism and surface leakage with a lower activation energy³⁹. Therefore, the surface leakage current suppression technique, such as surface passivation, could decrease the dark current density of the detector⁴⁴.

Figure 3. (a) The setup of the photoresponsivity measurement using a black body and lock-in amplifier. The inset is the optical image of a packaged InSb photodetector. (b) The temperature dependent photocurrent density of the detectors with different sizes from 80 K to 300 K. (c) Plot of photocurrent density vs. reverse bias from 0 V to 0.5 V for the detector with P/A of 127 and an exposed area of 0.0285 mm^2 .

Optical Property. Figure 3(a) shows the setup of the photocurrent measurement for the photodetector using a black body maintained at $700\text{ }^{\circ}\text{C}$. The light emitted from the black body was modulated by a mechanical chopper at 200 Hz. The photocurrent of the detector was amplified and the dark current was filtered by a lock-in amplifier that used the frequency of copper as a reference frequency. Figure 3(b) shows the photocurrent density of detectors with different P/A ratios when the V_{bias} is 0 V (i.e. photovoltaic mode). All of the detectors demonstrated a decreasing photocurrent density with an increasing temperature from 80 K to 300 K due to a shorter carrier lifetime in InSb layers at higher temperature⁴⁵⁻⁴⁶. The detector with the $\text{P/A}=40.2$ demonstrated a lower photocurrent density compared to others. As mentioned above, for the detector with a small P/A ratio, thermally generated carriers are unable to be collected by the ring-shaped electrode. This effect also occurred in photo-generated carriers. Therefore, a

high P/A (i.e. small exposed area) is essential for the InSb photodetector on Si and the detector with the P/A of 127 was selected for detailed study. Figure 3(c) shows an increased photocurrent density with an increase in V_{bias} at 80 K. Although the photocurrent density increased by a factor of 42 from $V_{\text{bias}} = 0$ V to 0.5 V, the corresponding dark current density increases by over 3 orders, as shown in Figure 2(a). An increase in the photocurrent of a p-i-n photodetector under a reverse bias could be attributed to the increased carrier collection efficiency⁴⁷. Another possible explanation is that the detector operated at the photoconductive mode. The photoconductive gain resulted in an increase in the photocurrent⁴⁶ because of the high J_{dark} at $V_{\text{bias}} > 0$ V.

Figure 4. (a) Spectral responsivity of the InSb photodetector as a function of wavelength at different temperatures. (b) The detail of the wavelengths near the absorption edge of InSb at different temperatures with normalized curves. (c) The absolute spectral responsivity, quantum efficiency, and (d) calculated spectral detectivity of the InSb photodetector at 80 K.

Figure 4(a) shows the spectral responsivity of the InSb photodetector with the exposed area of 0.0285 mm² from 80 K to 200 K with the step of 20 K. The range of

measurement is from 2.0 μm to 6.6 μm at 0 V of bias voltage (i.e. photovoltaic mode). An atmospheric CO_2 absorption peak at 4.2 μm was observed in each measurement. The weak responsivity at shorter wavelengths was due to the filtering effect of the n+ contact layer where most of the infrared light with shorter wavelength is absorbed by the n-type i layer and does not contribute to the photocurrent⁴⁸. The relative responsivities decreased dramatically with an increasing temperature. At 80 K, the highest responsivity was achieved around 5.3 μm . Figure 4(b) shows the details around the cutoff wavelength from 80 K to 200 K where the highest value of relative responsivities at different temperatures are normalized to 1. The 50% cutoff wavelength shifted from 5.7 μm at 80 K to 6.3 μm at 200 K due to the change in the bandgap of InSb.

To obtain the absolute value of responsivity, a calibrated commercial InSb photodetector operated at 77 K with a known 5.3 μm responsivity and active area was used. Through comparing the measured responsivity of the commercial InSb detector and the fabricated InSb detector on Si, the absolute value of responsivity and quantum efficiency (QE) at 80 K was shown in Figure 4(c). The highest responsivity was about 0.7 A/W, which was achieved around 5.3 μm , which corresponded to a QE of 16.3%. The electrical characterization of the InSb detector indicated its J_{dark} was mainly contributed to the thermally generated carrier caused by generation-recombination mechanism, therefore, the Johnson-noise can be considered as the main noise source²². The output noise (I_n)⁴⁹ can be calculated using $\sqrt{4k_B T R_0}$ where k_B is the Boltzmann constant, T is the device temperature (80 K), and R_0 is 905 Ω for this detector. The output noise is calculated to be 2 nV/Hz^{1/2}. Based its definition²², the D^* can be express as

$$D^* = \frac{R_v(A\Delta f)^{1/2}}{I_n} \quad (3)$$

where R_v is the responsivity with the unit of V/W, A is the mesa area (0.000787 cm^2) of the detector, and Δf is the bandwidth which is equal to 1 Hz in this calculation. R_v can

be calculated using $R_p \times R_0$ where R_p is the measured responsivity with the unit of A/W and its value at 5.3 μm is 633.5 V/W. The 80 K D^* at 5.3 μm is calculated to be $8.8 \times 10^9 \text{ cmHz}^{1/2}\text{W}^{-1}$. Based on this analysis, if the main noise source is Johnson-noise, the eq 3 can be rewritten as

$$D^* = R_p \left(\frac{R_0 A}{4k_B T} \right)^{1/2} \quad (4)$$

The calculated detectivity at 80 K is shown in Figure 4(d). The maximum D^* of $8.8 \times 10^9 \text{ cmHz}^{1/2}\text{W}^{-1}$ was achieved at 5.3 μm . This detectivity was about one order lower than that of the InSb photodetector on an InSb substrate⁵⁰.

Based on these results, a higher D^* could be achieved in three possible ways. The first way is by optimizing the barrier layer. An important reason for the low D^* is a low $R_0 A$ associated with a high dark current. Although the 20 nm $\text{In}_{0.82}\text{Al}_{0.18}\text{Sb}$ barrier layer in this study increases 80 K R_0 from 247 Ω to 905 Ω , its effect is much lower compared to the 100 nm $\text{InAs}_{0.18}\text{Sb}_{0.82}$ barrier layer in an InAs detector, where the 105 K $R_0 A$ was increased by six orders compared with the InAs detector without a barrier layer²⁹. The ideal barrier layer is able to suppress all surface leakage current and make the $R_0 A$ of the detector near “Rule-07”²⁹. The Rule-07 assumes all dark current is Auger-limited where the 77 K $R_0 A$ is $6.07 \times 10^9 \Omega/\text{cm}^2$ for the detector with the cutoff wavelength of 5.7 μm ⁵¹. The structure of the barrier layer could be further optimized. For example, a 70 nm $\text{In}_{0.8}\text{Al}_{0.2}\text{Sb}$ layer was used as the barrier layer in an nBn InSb photoconductor⁵². Moreover, optimizing the growth process of the barrier layer to avoid additional defects is also important. Second, apart from low $R_0 A$, the low QE (16.1% at 5.3 μm) is another reason for the low D^* . A simulation where hole diffusion length is assumed to be 5 μm indicates that the highest QE can be achieved when the absorption layer thickness is 4 μm . Moreover, the simulation also suggests that a higher hole diffusion length results in a higher QE. Therefore, the threading dislocation density should be further decreased⁵³ (the simulation is given in Section IV in the Supporting Information). Third, a higher D^* could be achieved by applying surface passivation on the detector. Beside

further increasing D^* , integration of the Si-based waveguide and this InSb detector on a single Si platform is also important. A similar waveguide structure with SiGe waveguide coupled SiGe quantum well detector can be considered⁵⁴. For the heteroepitaxial structure demonstrated in this paper, Ge buffer on Si can be etched to form Ge-on-Si waveguide due its low loss in the MIR region⁵⁵.

■ CONCLUSION

In conclusion, InSb p-i-n photodetectors with an electron barrier layer of $\text{In}_{0.82}\text{Al}_{0.18}\text{Sb}$ were successfully integrated on a 6° offcut (100) Si substrate via a GaAs/Ge buffer. Material characterization indicated that the InSb layer on Si has a low-defect density due to the low-defect GaAs/Ge buffer and an IMF array at the InSb/GaAs interface. The temperature dependent I-V curves suggested that the dark current generating mechanism was attributed to both the G-R mechanism and surface leakage at a temperature above 140 K and only surface leakage at a temperature from 120 K to 20 K. Below 20 K, carrier tunneling was the main mechanism. A 20 nm $\text{In}_{0.82}\text{Al}_{0.18}\text{Sb}$ electron barrier layer increased the 80 K R_0 of the InSb photodetector on Si from 247 Ω to 905 Ω . The photodetector had a 50% cutoff wavelength of 5.7 μm at 80 K and 6.3 μm at 200 K. At 80 K, the highest responsivity of 0.7 A/W, quantum efficiency of 16.3%, and detectivity of $8.8 \times 10^9 \text{ cmHz}^{1/2}\text{W}^{-1}$ were achieved around 5.3 μm . With further growth and device design developments, the InSb photodetector on Si is a potential component of mid-infrared silicon photonics.

■ METHODS

Heteroepitaxial Growth. The epitaxial structure of the InSb photodetector on Si is shown in Figure 1(a), which includes a Si substrate, Ge and GaAs buffers, and an InSb layer. The Ge-on-Si substrate was prepared through depositing 450 nm Ge on a (100) Si substrate with a 6° offcut towards $\langle 111 \rangle$ by chemical vapor deposition (CVD). The detailed growth process can be seen elsewhere¹¹. Growth of III-V compound semiconductor layers was carried out using a solid-state MBE system. The Ge-on-Si

substrate was firstly annealed at 650 °C for 20 minutes to form double atomic steps on the surface to suppress the APB in the GaAs buffer. After annealing, the substrate was cooled to 250 °C for the growth of a 10 nm GaAs buffer using migration-enhanced epitaxy (MEE). Subsequently, the substrate temperature was raised to 330 °C for the growth of a 40 nm GaAs buffer with a growth rate of 100 nm/hrs. Finally, the temperature of the substrate was raised to 580 °C for the growth of a 150 nm GaAs buffer with a growth rate of 1000 nm/hrs. A 100 nm InSb buffer was grown on a GaAs buffer using the IMF method (see the details of the growth process in Section I in the Supporting Information). The growth rate of InSb was 0.72 $\mu\text{m/hr}$ s with a V/III ratio of 3. Subsequently, the structure of the InSb photodetector device was grown. Be and Si dopants were used as the p-type dopant and n-type dopant, respectively. The doping level in each layer is shown in Figure 1(a). The i-layer was not intentionally doped with a background n-type doping level of about $2 \times 10^{16} \text{ cm}^{-3}$. The $\text{In}_{0.82}\text{Al}_{0.18}\text{Sb}$ layer was grown on InSb at 310 °C as a barrier layer due to its larger energy bandgap compared to that of InSb^{56} and a nearly zero valence band offset between $\text{In}_{0.82}\text{Al}_{0.18}\text{Sb}$ and InSb^{30} . The structural properties of InSb layer on Si were characterized using atomic force microscope (AFM), high resolution x-ray diffraction (XRD) and cross-section transmission electron microscopy (TEM).

Device Fabrication. The InSb photodetector was fabricated using a standard photolithography process, mesa etching, and electron beam-evaporated metal contacts. The InSb mesa was formed using a wet etch process with a citric acid and H_2O_2 etchant solution (the ratio of citric acid and $\text{H}_2\text{O}_2=33:2$ by weight). The etching depth was about 2400 nm. Au (150 nm)/Ti (30 nm) contacts were formed on n^+ and p^+ InSb contact layers, respectively. Detectors with different sizes were fabricated. No surface passivation or antireflection coating was applied on these devices.

Device Measurement. The photodetectors were mounted in a liquid nitrogen cooled optical cryostage for the measurement from 77 K to 300 K. The electrical properties of InSb detectors were obtain using a semiconductor device analyzer (Agilent Technologies B1500A). A black body and a Fourier Transform infrared spectroscopy

(FTIR) with a KBr beam splitter were utilized as the light sources for the photoresponsivity measurement, respectively. The system for measuring photoresponsivity under the black body has already been shown in Figure 3(a). For the measurement of photoresponsivity using FTIR, the output power spectrum of FTIR was measured using a thermopile detector (ThermoOriel Model 70124 with KRS-5 window), which has a flat response from 0.9 μm to 11.0 μm . The built-in photodetector of FTIR was replaced by one of the fabricated InSb photodetectors and its output signal was used to obtain its responsivity. All measurements were carried out under atmospheric pressure.

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■ ASSOCIATED CONTENT

Supporting information is available: (1) RHEED observation during the growth of InSb; (2) The composition of the InAlSb barrier layer; (3) The microstructure of the IMF array. (4) Simulation of the InSb photodetector. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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