

Low leakage-current InAsSb nanowire photodetectors on silicon.

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Abstract

Axially doped $p-i-n$ InAs_{0.93}Sb_{0.07} nanowire arrays have been grown on Si substrates and fabricated into photodetectors for shortwave infrared detection. The devices exhibit a leakage current density around 2 mA/cm² and a 20 % cutoff of 2.3 μm at 300 K. This record low leakage current density for InAsSb based devices demonstrates the suitability of nanowires for the integration of III-V semiconductors with silicon technology.

Keywords Nanowires, mid-wavelength infrared, photodetector, InAsSb

The integration of III-V semiconductors with silicon substrates targets the compelling goal of photonic devices combined with mature silicon technology.^{1,2} However, heteroepitaxy of bulk III-V materials on silicon substrates results in high defect levels which reduce the crystalline quality and performance of such devices.³ Nanowires have been shown to overcome this problem due to rapid strain reduction during growth leading to lower dislocation densities.^{3,4} In this work a shortwave infrared InAsSb nanowire photodetector is grown on silicon, incorporating an axial *p-i-n* junction and exhibiting an exceptionally low leakage current density of less than 2 mA/cm² at 300 K. Significantly, this new technology has a much lower leakage than today's best InAs(Sb) photodiodes, which have reported leakage current densities around 100 mA/cm² at 300 K, despite their increased bandgap and homoepitaxial substrates.⁵⁻⁸ In doing so it paves the way for lower noise III-V detectors, which can further benefit from intimate integration with silicon electronics technology.

Nanowires made from InAs and InAsSb are typically grown using Metal Organic Vapour Phase Epitaxy (MOVPE) and Molecular Beam Epitaxy (MBE) using the Vapour-Liquid-Solid (VLS)⁹ growth mechanism which uses a metal droplet (either gold or indium) as the nanowire seed. In our work we use a catalyst free method¹⁰ which begins with lithographic patterning using electron beam lithography (EBL)¹ followed by wet etching holes in the native oxide of the Si substrate. We then grow the nanowires by MBE and rely on the holes in the oxide to localise the nanowire growth to defined locations. The advantages to this method are the avoidance of gold, which forms trap states in silicon,^{2,11} and simpler growth as there is no need to optimise droplet deposition. The native oxide also prevents material deposition between the nanowires which is typical of growth on unpatterned Si substrates.¹² Although EBL is slow and costly, nanoimprint lithography^{13,14} will allow for low cost patterning of large area devices. By controlling the site locations, nanowire groups can then be used as individual photonic devices such as pixels in focal plane arrays or ultra-small detectors.

Figure 1a shows an atomic force microscope (AFM) image of the patterned holes in the

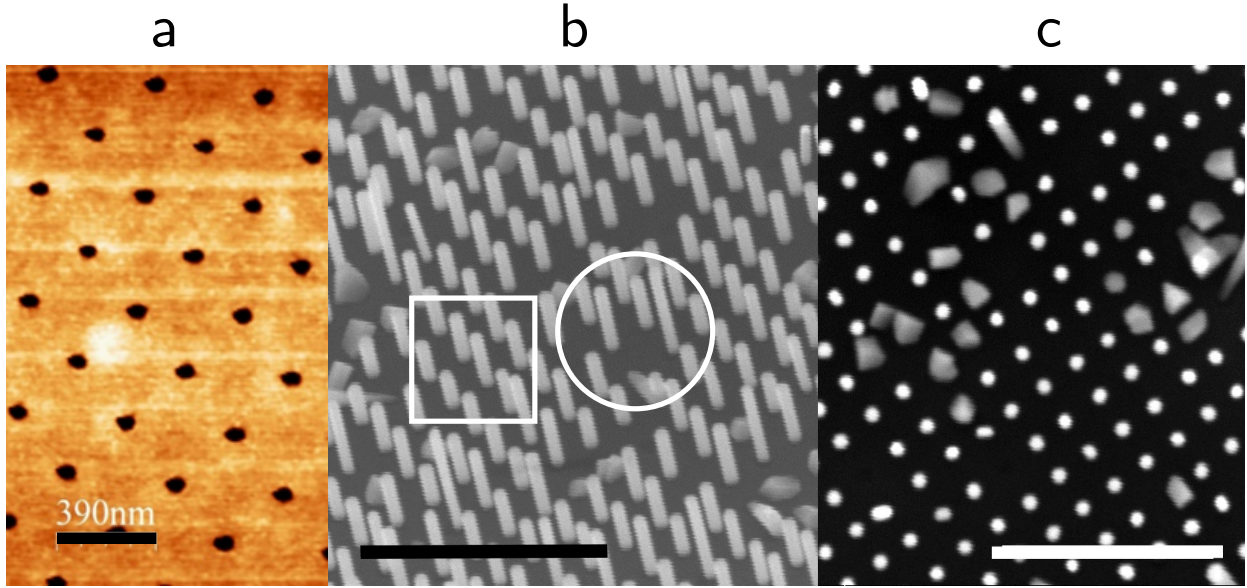


Figure 1: Patterned InAsSb Nanowires. (a) Atomic force microscope (AFM) image of the etched holes in the oxide layer on the substrate. Scale bar: 390 nm. (b) SEM image with 30° tilt of InAsSb nanowires grown in the holes in the oxide layer. The square and circular outlines indicate regions of uniform and non-uniform growth. Scale bar: 2 μm . (c) Top view SEM image of patterned InAsSb nanowires with highly uniform nanowire diameter. Scale bar: 2 μm .

resist before wet chemical etching. The holes are around 50 nm in diameter patterned into a 300 nm pitch square array. Figures 1b and 1c show scanning electron microscope (SEM) images of InAsSb nanowires grown with this pattern that are on average about 1 μm in length and 80 nm in diameter and the area fraction occupied by the nanowires is approximately 10%. From SEM analysis of various samples we have found that in cases where a nanowire fails to grow, nearby wires have a greater length variation (circular outline in figure 1b) and are typically longer because of proximity effects.¹⁵ This is due to the small pitch of the patterned array being less than twice the diffusion length of indium adatoms on SiO_2 , which is estimated to be ~ 750 nm.¹⁶ As a result, each nanowire is within the capture area of nearby wires. When a hole is not fully etched and no nanowire grows at that location, the indium adatoms diffuse to neighbouring nanowires leading to an increase in their growth rate. In regions of more successful growth the wire length is more uniform as seen in the square outline in figure 1b. For uniform length distribution in dense arrays it is therefore

crucial that all holes are cleanly etched.

For device applications, it is important that the nanowire is grown directly onto the substrate to provide electrical contact and avoid any series resistance due to the presence of an oxide layer between the nanowire and the substrate. For this work we have grown nanowires using InAs and InAsSb. Figure 2a shows a low magnification annular dark field scanning transmission microscopy (ADF-STEM) image of a nanowire grown on the silicon substrate. Site specific specimen preparation to analyse the nanowire/substrate interface by electron microscopy was achieved using focused ion beam (FIB) lift-out. Figure 2c shows a high magnification ADF-STEM image of the interface between an InAs nanowire and the Si substrate which shows that the nanowire has grown directly on the substrate. Furthermore, the InAs has the characteristic mix of wurtzite (WZ) and zinc-blende (ZB) phases^{17,18} whilst the InAsSb nanowire (figure 2b) is ZB, as expected.¹⁹ A polytype phase as seen in InAs can lead to unwanted uncontrollable heterostructures due to the different bandgaps of the ZB and WZ phases.²⁰ The addition of Sb forces a ZB phase with ortho twins which do not change the polarity of the crystal along the nanowire. Compositional analysis (see supplementary figure 1) along the length of an InAsSb nanowire revealed that the base of the wire contains a 20 nm section of polytype InAs suggesting that the incorporation of Sb is suppressed during the early formation of the nanowire. The reason for this is not yet understood.

A lab-setup XRD system was used to determine the composition of the $\text{InAs}_{1-x}\text{Sb}_x$ nanowires by performing a 2θ - ω scan of the 111 reflection of the as-grown sample (see figure 2 d). The peak position corresponds to an Sb composition of $x = 0.07$ which is calculated using the position of the InAsSb peak relative to the substrate peak and is in good agreement with the results from photoluminescence. To ensure that the XRD peak originates from nanowires and not surface growth, several scans with different θ offsets have been performed showing only a slight decrease in intensity (see inset of figure 2d). Due to the small diameter of the nanowires their diffraction peaks have a larger in-plane broadening compared to surface growth for which only a small θ offset is sufficient to decrease the intensity considerably.

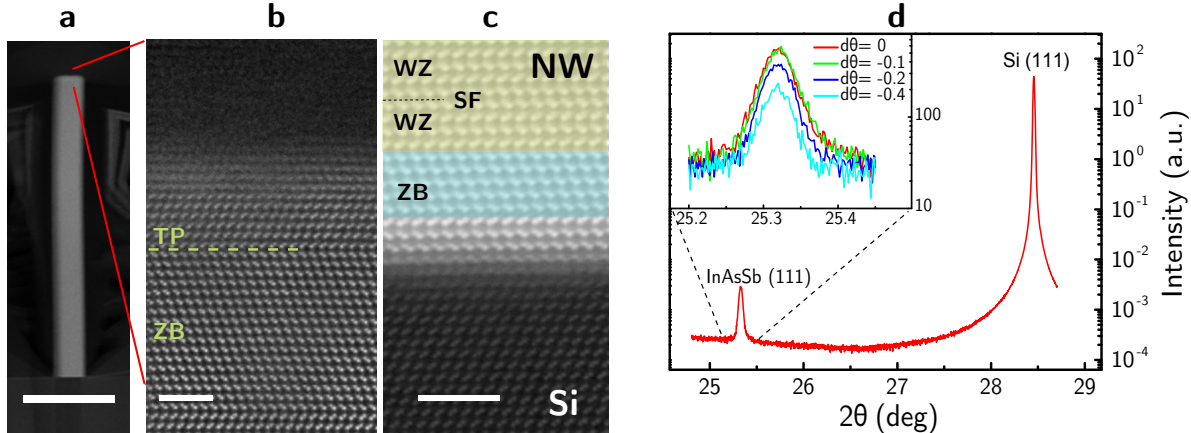


Figure 2: Structural characterisation of InAsSb nanowires. (a) Low magnification ADF-STEM image of InAsSb nanowire. Scale bar: 500 nm. (b) The top of the nanowire is flat and shows the multi-twinned ZB structure of the InAsSb. Scale bar: 2 nm (c) High magnification ADF-STEM image corresponding to the InAs nanowire/Si interface shows that the nanowires have grown directly onto the substrate and InAs section shows a mix of WZ (with stacking fault (SF) indicated by the dashed line) and ZB regions. Scale bar: 2 nm (d) XRD rocking curve of $\text{InAs}_{0.93}\text{Sb}_{0.07}$ nanowires on (111) Si substrate. Inset: The InAsSb peak for different θ offsets which shows only a slight decrease in intensity indicating that the peak originates from the nanowires and not from planar material.

Nanowire photodetectors were fabricated by growing an axial p - i - n structure consisting of 250 nm p -type (Be doped) InAs followed by 500 nm p -type InAsSb, 500 nm undoped InAsSb and finally 500 nm n -type (Te doped) InAsSb. The schematic of a finished device is shown in figure 3a which highlights the different sections of the nanowire. Below this, in figure 3b, is a band diagram at zero bias for the full structure. In devices where the junction occurs at the interface between the nanowire and the substrate, the band offsets between the nanowire and silicon can significantly hinder the movement of the carriers. By growing a p - i - n structure, the voltage drop principally occurs across the intrinsic region of the nanowire, from where the photo-generated carriers can drift easily into the majority carrier regions.

The leakage current measured at room temperature is shown in figure 4. At a typical detector operational bias of -0.1 V the reverse leakage current was 18 pA, which corresponds to a current density below 2 mA/cm² for the 200 nanowires contacted by the metal. This result shows the nanowire photodetector to have significantly lower noise due to leakage current compared to conventional InAs(Sb) detectors, despite being grown on a heavily

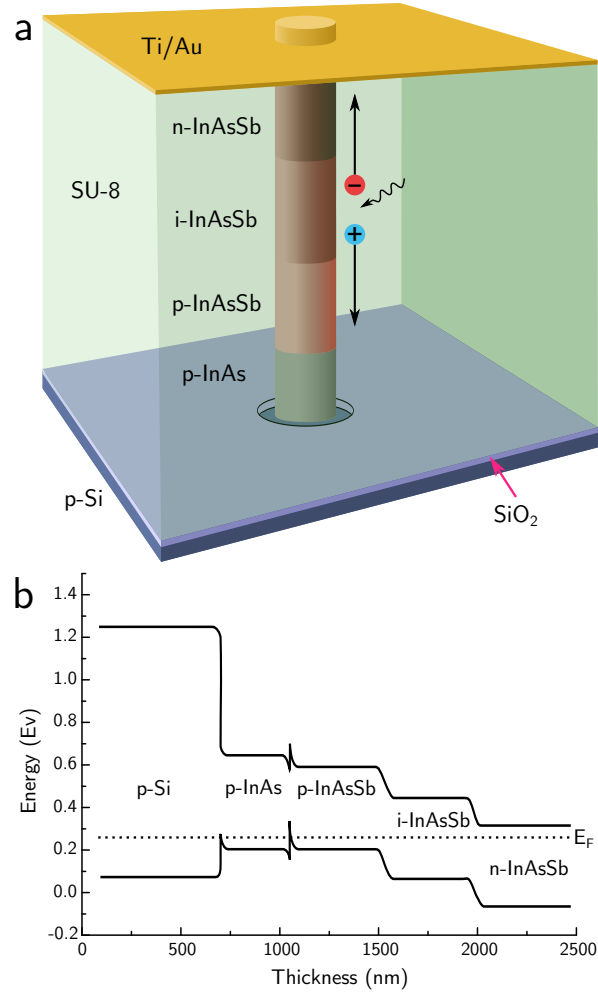


Figure 3: Schematic of $p-i-n$ InAsSb nanowire photodiode. (a) The nanowire consists of a 200 nm Be doped InAs stub followed by 500 nm Be doped InAsSb, 500 nm undoped InAsSb and 500 nm Te doped InAsSb. The nanowire is encapsulated by cross-linked SU-8 with Ti/Au forming the top contact. (b) Band diagram of the $p-i-n$ photodiode at zero-bias.

mismatched substrate.

The forward bias current can be fitted well as an ideal diode, with an ideality factor of 1.4, and a simple series resistance. This indicates that the current-voltage characteristic is dominated by a single type-junction. Furthermore the series resistance fitted is two orders of magnitude lower than the dynamic resistance in reverse bias, at -0.1 V, confirming that it cannot be the cause of the exceptionally low reverse leakage current density. Photocurrent was measured under illumination by a 14 mW $1.55 \mu\text{m}$ laser, however due to the continuous, optically opaque top contact covering the nanowire array, this was not directly incident

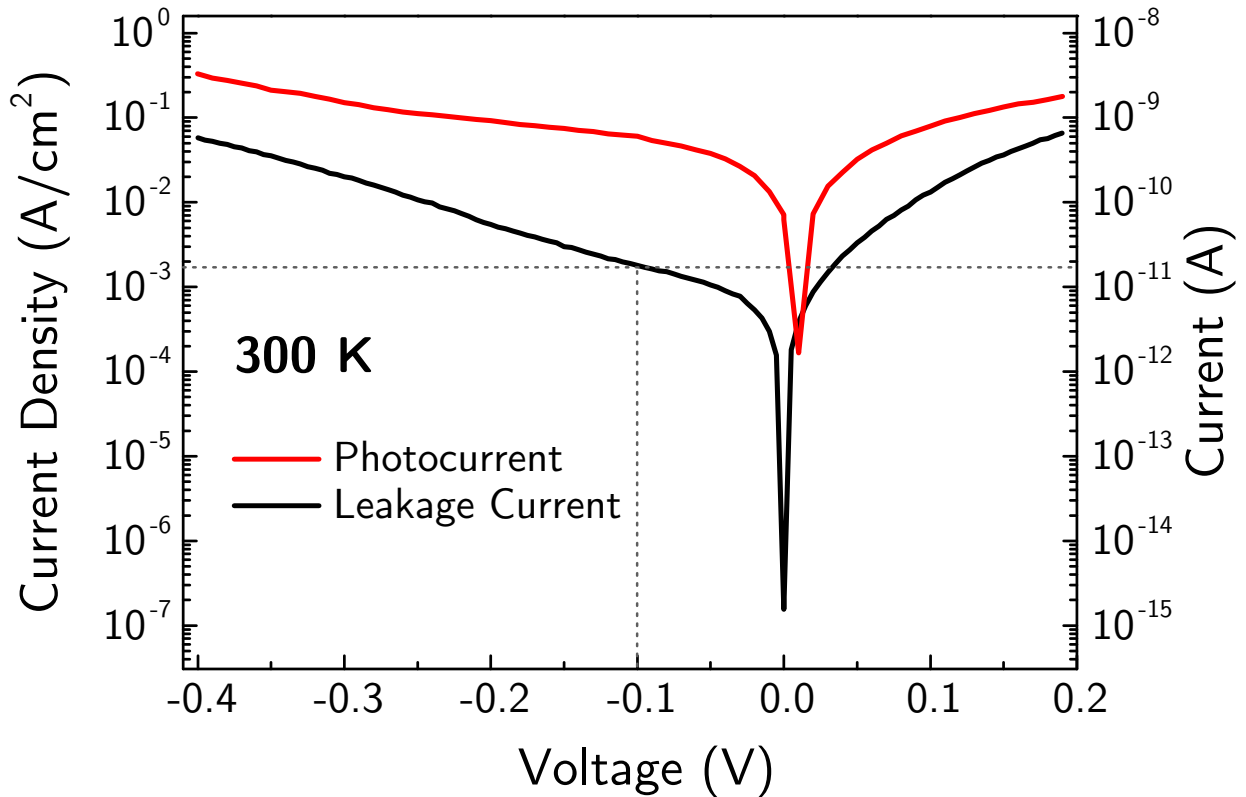


Figure 4: Semi-log current-voltage characteristic of $\text{InAs}_{0.93}\text{Sb}_{0.07}$ *p-i-n* photodiode at 300 K with nanowire diameter of 80 nm and length 1.7 μm . The black and red plots show the leakage current and photocurrent density respectively for 200 contacted nanowires. At a typical operational bias of -0.1 V the leakage current is 18 pA which corresponds to a leakage current density around 2 mA/cm². For photocurrent measurements, illumination was provided by a 1.55 μm laser to which the substrate is transparent.

on the nanowires. Instead it was fibre coupled onto an area adjacent to the edge of the contact, from where a small fraction was coupled into the wires through scattering and interface reflections. As seen in figure 4, a photocurrent was detected which indicates that the nanowires are optically active, however due to the optically opaque top and bottom contacts the nanowires can only be indirectly illuminated at this time, hence it is not yet possible to determine the quantum efficiency. Prior studies have been made of InAsSb nanowires with higher Sb fractions, configured for infrared photodetection. Without any type of junction these photoconductive wires showed some response, however despite cooling to 5 K, leakage remained in the mA range for ~ 8000 wires.²¹

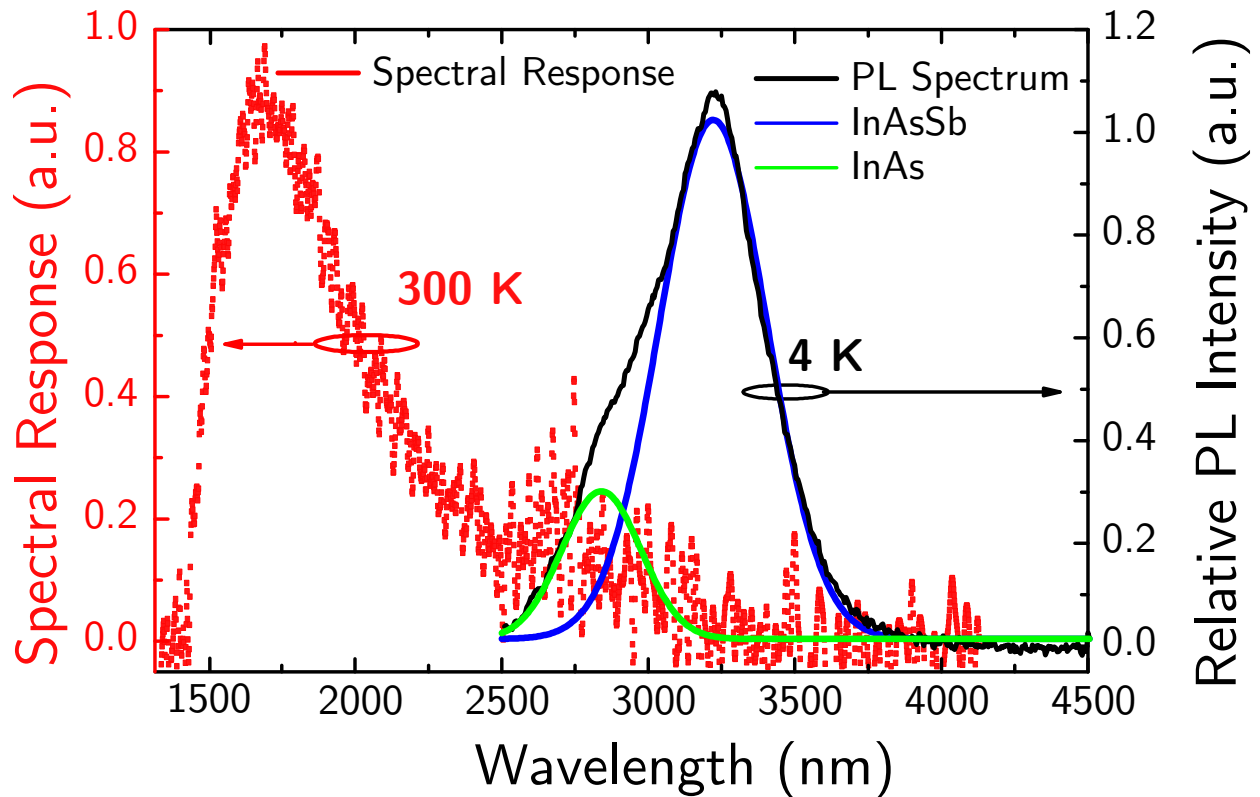


Figure 5: Spectral response at 300 K and -0.1 V bias (red) and 4 K photoluminescence spectrum (black) of $\text{InAs}_{0.93}\text{Sb}_{0.07}$ nanowires. The PL spectrum is de-convoluted using two Gaussian peaks to show the contributions of the InAs (green) and InAsSb (blue) sections of the wire. The noise in the spectral response between 2500 and 3000 nm is an artefact of the system response correction due to atmospheric absorption.

The 300 K peak spectral response in figure 5 is significantly shorter than the photoluminescence (PL) peak which we attribute to the wavelength and wire diameter dependence of the HE₁₁ mode in the nanowires.²¹ Increasing the absorption strength for longer wavelengths can be achieved by optimising the nanowire diameter and since our aim is to detect in the mid-infrared, this will be the focus of future work. For PL measurements, undoped nanowires were grown with the dense pattern shown in figure 1a containing an initial 200 nm InAs section followed by 800 nm of InAsSb. The overall PL peak, see figure 5, consists of emission from both the InAs and InAsSb sections at 2850 nm and 3240 nm respectively. The emission from the InAs is blue shifted from the expected wavelength by around 5 meV which is consistent with confinement in a 80 nm 1D quantum wire.^{22,23}

Optimisation of the length and diameter of InP nanowires has been shown to increase the absorbance of nanowire arrays to levels which equal planar devices despite having only a fraction (10%) of the volume.²⁴ Assuming equal absorbance, 10% nanowire coverage and the observed leakage current density reduction of 50 times, InAsSb nanowire photodetectors could increase the SNR by up to 500 times over conventional InAs(Sb) photodetectors.

InAs based photodiodes have long been known to suffer from high levels of surface leakage originating from an electron accumulation layer, such that, as the perimeter to area ratio increases, surface leakage tends to dominate the total leakage current.⁵ The perimeter/area ratio of the nanowires in this work is extremely high at $5 \times 10^5 \text{ cm}^{-1}$. Ker et al. separated surface and bulk leakage in InAs photodiodes and reported them as a function of temperature.⁵ Comparison with these results shows that conventional InAs photodiodes with the nanowire's dimensions would indeed be strongly dominated by surface leakage. Only by cooling to 125 K would this surface leakage current fall to the levels of the total leakage measured in these nanowires at 300 K. Defining a mesa diode requires the removal of material through chemical etching, which disrupts the lattice and allows impurities to be introduced. By using monolithically grown nanowires to define the detecting volume, the surfaces remain unmodified and defect free which we believe leads to a reduction in the surface contribution to the overall leakage current. Even if surface leakage is neglected, cooling to 230 K would be required for the best InAs photodiodes to match the leakage current density measured in the nanowires at 300 K.

Bulk leakage current density is closely associated with the crystalline quality of the detector material and hence it is inferred that the nanowire material exceeds the quality of conventional epitaxial InAs(Sb). This is supported by TEM analysis, which shows twinning of the zinc-blende lattice, but an absence of threading defects. The nanoscale diameter of the wires ensures that any 60° threading dislocations originating from the interface with the (111) Si reach a sidewall and terminate within the lower 150 nm of the wire. Hence the crystalline structure of the wire in the region of the *p-i-n* junction is expected, and observed,

to be entirely free from any leakage-causing defects.

In summary, we have fabricated shortwave infrared photodetectors, using site-controlled nanowires on silicon, with unprecedentedly low leakage current at room temperature. Not only has this allowed for high quality shortwave infrared photodetectors to be grown on silicon substrates, but surprisingly, the leakage current density is almost two orders of magnitude lower than state of the art InAs(Sb) photodiodes. The unique design also allows for electrical conduction through the substrate which simplifies many aspects of the fabrication and expands the opportunities for integration. Although the nanowires occupy only a small fraction of light collection area, optimisation of the length and diameter^{24,25} can significantly increase the absorbance up to that of planar films.^{2,24} Combined with the reduction in leakage current density over InAs(Sb), this should provide a more than two orders of magnitude increase in SNR over state of the art InAs(Sb) devices. This result is the first reported InAsSb nanowire photodiode and the lowest leakage current density reported for any InAs(Sb) photodiode at 300 K. We believe that this represents a major step towards high-performance mid-infrared photodetectors compatible with silicon technologies and which can be integrated with other photonic systems.

Methods

Nanowire Growth The nanowires were grown on Boron doped (111) orientated Si substrates with a known oxide thickness of either 20 or 50 nm. The substrates were spin coated with PMMA and then patterned using electron beam lithography using a hole diameter of 50 nm. After development the substrates were wet etched using 10:1 buffered oxide etch (BOE) to remove the oxide within the exposed holes. The resist was then removed and the substrates were dipped in BOE once more to ensure a stable surface²⁶ before being loaded immediately into the MBE reactor. The nanowires were grown using a VG V80h MBE reactor and 2D growth rates for In, As and Sb were calibrated using (001) InAs, GaAs and InSb respectively. The In 2D growth rate was set to 0.07 ML/s with As at 1.8 ML/s and Sb at 1.15 ML/s which gives a V-III ratio of 42:1. The substrate was initially heated to

600 °C without any group V flux before being cooled to the growth temperature of 480 °C. The nanowire growth was then initiated by simply opening the In, As and Sb shutters. All samples in this report are grown with the same Sb composition. Dopant cell temperatures were set according to the measured concentrations in 2D InSb of $7 \times 10^{17} \text{ cm}^{-3}$ for Be and $5 \times 10^{17} \text{ cm}^{-3}$ for Te.

Photodetector Fabrication To fabricate the photodetectors, the substrates were spin coated with 2 μm thick SU-8 and flood exposed to harden the resist. The resist was then etched using reactive ion etching in CF_4 and O_2 to expose the tips of the wires. The wire tips were then contacted using 30 nm Ti and 200 nm Au with 200 nm Al on the back of the substrate forming the back contact. The schematic of a finished device is shown in figure 3a showing the different sections of the nanowire.

Spectral Response and Current Voltage measurements Spectral response measurements on the photodetectors were performed using a Bruker Vertex FTIR at room temperature and a bias of -0.1 V.

Leakage current measurements were carried out using a Lakeshore TTPX probe station with guarded triaxial connectors and a Keithley 6430 Sub-Femtoamp SourceMeter. A source delay of 10 sec was used to prevent transient triboelectric or piezoelectric effects from influencing the measurement. The measured leakage current at room temperature, shown in figure 4, at a typical operational bias of -0.1 V was 18 pA. However, due to variation in nanowire length, not all of the wires were exposed after etching back the resist.

To determine the number of wires contacted, we used SEM to assess the fraction of wires exposed after etching. The metal contact covered a portion of a large low density nanowire array with a pitch of 2 μm . Areas of nanowires adjacent to the contact were imaged with the image field of view covering approximately 230 nanowires. Two images of this type were taken and the number of nanowires which protruded above the surface of the the SU-8 were counted in both images to determine the fraction which were exposed. (See supplementary figure 2 for an example of both an exposed and a covered nanowire.) Using this method we

determined that approximately 15 % of the wires were exposed. The metal contact covered an area containing around 1500 wires which would mean that approximately 200 wires were contacted by the metallisation. The cross-sectional area was estimated using the nanowire diameter and approximating to a circular cross-section.

Photoluminescence The sample was cooled in a continuous flow liquid helium cryostat to 4 K and excited with a 808 nm laser with excitation power of 150 mW. The spectrum was recorded using a Bentham TMc300 monochromator with InSb detector.

Transmission Electron Microscopy Annular dark field (ADF) scanning transmission electron microscopy (STEM) images were taken in an aberration-corrected JEOL ARM-200F microscope working at 200 kV. Focused ion beam (FIB) lift-out TEM specimens to investigate the interface with the substrate were prepared using a JEOL JIB4500.

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Author Contributions

M.D.T., A.A. and A.R.J.M. conceived the project, designed the arrays and performed the MBE growth. A. Aziz patterned and developed the wafers before growth. M.D.T. fabricated

the photodetectors. A.R. performed the AFM analysis. A.P.C. and M.D.T. performed the spectral response and current-voltage measurements. A.A. and A.K. were responsible for photoluminescence. J.S. and L.W. provided xray analysis. A.M.S. provided TEM analysis. M.D.T. and A.R.J.M. co-wrote the paper.

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Competing financial interests

The authors declare no competing financial interests.

Additional Information

All the data used for the plots in this work are publicly available at:
<http://dx.doi.org/10.17635/lancaster/researchdata/51> .

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Supporting Information Available

Figure of energy-dispersive x-ray (EDX) spectrum of InAsSb nanowire on Si substrate and figure of exposed nanowire after etching back SU-8.

This material is available free of charge via the Internet at <http://pubs.acs.org/>.

Graphical TOC Entry

