Narrowband photodetection from visible to infrared wavelengths using germanium nanowires

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ABSTRACT

At visible wavelengths, photodetection in three channels (red, green and blue) enables color imaging. Yet the spectra of most materials provide richer information than just color, and therefore considerable interest exists for imaging with multiple spectral bands across the visible to infrared. This endeavor requires narrowband photodetection, which is generally achieved by combining broadband photodetectors with filters or spectrometers, but with added bulk and cost. Here we report, for the first time to our knowledge, vertical germanium nanowires as narrowband photodetectors. Our devices exhibit spectral response peaks that are as narrow as 40 nm and can be shifted from visible (~600 nm) to infrared (~1600 nm) wavelengths by appropriate design. The spectral selectivity arises from the nanowires acting as waveguides and, surprisingly, is enhanced by radial narrowing of the carrier collection region due to surface recombination. The incorporation of germanium into integrated circuits in a high yield and cost-effective manner is well-established, making our approach promising for many detection applications.

KEYWORDS
Nanowires, Optical Physics, Near-infrared spectroscopy, Photonic devices
Conventional photodetectors typically feature broadband spectral responses because semiconductors absorb photons with energies greater than their bandgaps, in a manner dictated by Fermi’s golden rule\(^1\). Spectrally-selective photodetection involves splitting this broad absorption window into multiple bands. In color imaging, for example, coating an array of broadband photodetectors with red, blue or green filters\(^2\) enables selective detection of different colors, similar to the human eye. Yet the spectra of materials and scenes provide a wealth of information not present in simple color images. This has motivated the development of multispectral and hyperspectral imaging, due to the myriad of applications that they enable, such as in food safety control\(^3,4\) and in remote sensing, for example for crop productivity determination\(^5\) and to monitor leakage from CO\(_2\) sequestration sites\(^6\). Many multispectral systems exist in nature. The eyes of the mantis shrimp, for example, have as many as 16 types of color receptor cones\(^7\), which is advantageous for the demands of underwater vision.

Multispectral imaging is particularly important in the short wave infrared (SWIR) spectral region, due to numerous applications\(^8\), for example in the semiconductor industry\(^9\) and in biology and medicine\(^10\). Such systems frequently rely on optical filters or monochromator assemblies that act as narrow bandpass filters\(^8\). A multispectral response is obtained by scanning the entire input spectrum with a narrowband window. While such input filtering systems can accommodate a large number of bands, the extraneous components involved render the system bulky and expensive. Further, such sensors employ costly III-V semiconductor\(^11\) that pose issues around CMOS compatibility. To address the need for narrowband detection with filterless design, new directions have been proposed in the recent literature using organic dyes\(^12\), doped perovskites (via charge collection narrowing)\(^13\) and via plasmon induced hot carrier generation\(^14\). However,
these examples were limited to visible wavelengths for the dyes and perovskites, and to the SWIR region for hot carrier detectors. This limitation motivates the development of narrowband photodetectors that can be tuned across the visible to SWIR wavelength range by appropriate design, which we address in this work.

Nanowires (NWs) are an excellent candidate for narrowband detection due to their potential for spectrally selective light absorption, a consequence of waveguiding and resonance phenomena\textsuperscript{15–17}. In previous work, we demonstrated that such phenomena be employed for the realization of transmission filters based on silicon nanowires at visible to near-infrared wavelengths\textsuperscript{18}. We demonstrated color imaging using silicon nanowire photodetectors\textsuperscript{19}. In other work, we demonstrated the tuning of dip features in the reflection spectra of germanium nanowire (Ge NW) arrays from visible to SWIR wavelengths\textsuperscript{20}. Here, we demonstrate narrowband photodetectors with peaks in external quantum efficiency (EQE) spectra that can be tuned from visible to SWIR wavelengths. We fabricate arrays of vertically-oriented Ge NWs containing p-i-n photodiodes. We measure the zero bias EQEs as a function of illumination wavelength of these arrays, each of which contains NWs of a certain diameter. Interestingly, the measured EQE spectra are narrower than would be expected from simulations of the absorption spectra of these structures. Through combined semiconductor device and electromagnetic modeling, we find that this results from surface states. Our results demonstrate photodetection that is highly spectrally-selective, spanning the wavelength range \(~600\) nm to \(~1600\) nm. Our devices, therefore, present exciting possibilities as pixels for multispectral image sensors.
Fabrication of our Ge NW array photodetector devices starts with a highly doped Ge wafer (p+), on which intrinsic and n+ doped layers are epitaxially grown. The NWs are then produced by electron beam lithography (EBL) and inductively coupled plasma reactive ion etching (ICP-RIE). In our previous work on Si NW photodetectors, electrical contact was made to the tops of the NWs using a layer of indium tin oxide (ITO), supported by a polymethylmethacrylate (PMMA) film that was several microns thick. The fact that the NWs were surrounded by PMMA rather than air (for example) lowers the refractive index contrast between the NW and the surrounding medium. In this work, we demonstrate a novel configuration for the top electrode. We use ITO to make electrical contact to the tops of the NWs. Rather than a flat film, however, the ITO wraps around the NWs but is electrically separated from them using alumina formed by atomic layer deposition (ALD). In this way, the NWs are surrounded by air (though with cladding layers of alumina, ITO, etc.) and the index contrast is higher than in our previous work. The ITO is further electrically isolated from the substrate using a thin PMMA layer, and a thin gold layer is also added. Further details on the fabrication process are provided in the Methods section and Supporting Information. Scanning electron micrographs (SEMs) of the NW arrays after etching and after completion of the fabrication process are shown in Fig. 1a(i) and (ii), respectively. An optical microscope image of completed devices is shown in Fig. 1a(iii). Some variation in coloration can be seen. We believe that this is due to variation in the thickness of the PMMA layer used to electrically isolate the ITO from the substrate and that this will have a negligible effect on the NW absorption spectra. Higher magnification SEMs of the NWs (Fig. 1a(iv)-(vi)) reveal that they are slightly tapered. This tapering is taken into account in the modeling work presented later in this paper. A schematic illustration of the completed device is shown in Fig. 1b. We experimentally demonstrate devices with NW diameters ranging from 75
to 250 nm. To avoid confusion, unless otherwise stated, all diameters mentioned in this paper are the design values used in the EBL step. The top and bottom diameters measured from the nanowires by SEM are provided in the Supplementary Information.

After fabrication is complete, the device is mounted on a printed circuit board, and electrical connections are established with gold wires and silver paste (Fig. 2a). A consequence of the fabrication process is that multiple NW array photodetectors are formed adjacent to one another, and are connected in parallel with a common top and bottom (substrate) electrodes. Our optical characterization set-up (Fig. 2b) however allows our NW array devices to be illuminated one-at-a-time, with light from a monochromator focused to a spot that is smaller than the device being measured. This approach enables us to measure the responsivity spectrum of each nanowire device separately. These spectra are presented later in this paper. In previous work on the resonant enhancement of absorption in Ge NWs, photoconductivity measurements were performed on undoped NWs\textsuperscript{15}. For many practical applications, photodiodes are preferred, however, for efficient carrier separation and to reduce dark current. This motivates us to form p-i-n junctions in our NW devices, enabling us to operate them in a photovoltaic mode without external bias. Current-voltage (I-V) measurements are shown in linear-linear and log-linear scales as Fig. 2c and Fig. 2d, respectively. Results are presented with the device in the dark and with illumination from the microscope associated with the probe station. All nanowire arrays are illuminated. From Fig. 2c-d, it can be seen that ideal diode behavior is not achieved. As discussed further in the Supporting Information, the ideality factor is \~4 and other processes such as carrier recombination dominate. Nonetheless, an on-off ratio of \~28:1 around zero bias is recorded under these illumination conditions (Fig. 2d). In Fig. 2e, we show the current measured...
from our NW device as a function of time, as the illumination is switched on and off. For these measurements, the illumination is again from the microscope on the probe station and all nanowire arrays are again illuminated. Our device shows a photocurrent of ~ 2.7 µA with zero bias applied. As an additional check, we move our sample so that the illumination spot is not impinging upon one of the NW arrays, but on another part of the sample. The measured photocurrent is at the background noise level. This suggests that in our device, the measured photocurrent is generated by the NW arrays and not by the other regions.

We next investigate the spectral response of our device. In previous work, we showed that NWs can exhibit spectrally selective absorption due to the wavelength-dependence of the field distribution of the guided modes\textsuperscript{16}. This guided mode absorption leads to peaks in the absorption spectra that can be tuned by modifications to the NW diameter\textsuperscript{16}, as discussed further in Supporting Information. This phenomenon has also been investigated further\textsuperscript{21} and for other applications, such as multiterminal spectral splitting\textsuperscript{22}. In Fig. 3a, we present simulations of the absorption efficiency vs. wavelength of arrays of Ge NWs. To facilitate understanding, these structures have simpler models than the actual devices. They consist solely of Ge NWs on Ge substrates and do not include the other materials that occur in the actual devices. The NWs are chosen to be tapered, with different top and bottom diameters, to represent the geometries of the fabricated devices. The NWs are in square arrays (1 µm period) and have heights of 2 µm. The absorption efficiency is the fraction of light absorbed by the part of the NW that would be the intrinsic region for the actual device. This region starts at 300 nm from the top of the NW and extends 1.5 µm below. As is done throughout this paper, unless otherwise stated, the diameters listed in Fig. 3a are nominal values used in the e-beam lithography design step. It can be seen
from Fig. 3a that the absorption spectra display peaks that can be tuned by changing the NW diameter. The spectra also display ripples at shorter wavelengths due to Fabry–Pérot resonances\(^{20,23}\). Sharp features occur around \(\lambda = 1000 \text{ nm}\), due to the coupling of light into periodic array/grating modes that occurs when the free space wavelength matches the array period. We next present experimental external quantum efficiency (EQE) vs. wavelength results (Fig. 3b), measured using the set-up shown in Fig. 2b. Following the same trend as the simulations of Fig. 3a, the measured EQE spectra exhibit peaks that shift to longer wavelengths with increasing NW diameter. Like the simulations, the measured spectra also show features around \(\lambda = 1000 \text{ nm}\), but not for all devices. Nonetheless, we do see noticeable differences between the experiment and our simulations. In experiments, fabricated devices show a peak EQE of \(~0.076\) (for NWs with diameter 200 nm), while simulations with an ideal geometry predict absorption efficiencies close to unity (Fig. 3a). Furthermore, measured EQE spectra show sharp narrowband peaks with full-widths-at-half-maximum (FWHMs) ranging from 40 to 155 nm. By contrast, simulations predict absorption efficiency spectral peaks with FWHMs ranging from 115 to 250 nm (Fig. 3a). We next consider two important differences between experiment and simulation that could account for this discrepancy. The first difference is that of the device structure (Fig. 1b) differing from the simple Ge NW arrays simulated in Fig. 3a. We next refine our simulations to match the actual devices as far as possible, i.e. including the alumina, ITO, Au, and PMMA layers. The results (Fig. 3c) however show absorption peaks that are not narrower, with FWHMs ranging from 160 to 385 nm. Furthermore, the discrepancy still remains that the experimental EQEs are much lower than the simulated absorption efficiencies. This leads us to consider the second difference. In comparing the simulated absorption efficiency to the EQE measurements, we are implicitly assuming that the internal quantum efficiency (IQE) is
unity, i.e. all photogenerated carriers are collected. For NWs, however, charge transport is strongly influenced by doping and the presence of surface and interface states\textsuperscript{23–26}. The surface and interface states arise from the termination of the semiconductor lattice at the surface of NW, which modifies the electronic potential and results in new electronic states that can trap charge carriers\textsuperscript{27–29}. We therefore modify our simulation to include electrical modelling. Further details are provided in Materials and Methods, as well as in the Supporting Information. It can be seen that the simulations that include both optical and electrical modelling (Fig. 3d) are in far better agreement with the experimental results. These simulations assume a surface trap density of 1E+13 cm\textsuperscript{-2}.

We next further investigate the influence of surface traps on the carrier transport in our Ge NWs. In Fig. 4a, we schematically illustrate the effect of surface states on the charge transport and recombination processes within the p-i-n junction of our Ge NWs. In Fig. 4b-f, we show key results of combined optical-electrical modeling. In Fig. 4b, we plot the simulated optical generation rate on a cross section along a NW whose geometry is chosen to match that of the fabricated device whose nominal (EBL design-value) diameter is 75 nm. This simulation is for excitation from a normally incident \(x\)-polarised plane wave (at \(\lambda = 710\ \text{nm}\)). In Fig. 4c, we plot the simulated charge collection probability (or IQE), defined as the fraction of photogenerated electron-hole pairs that are collected, for an assumed trap density of \(S = 1E + 12\ \text{cm}^{-2}\). We next find the carrier collection rate (Fig. 4d) by multiplying the optical generation rate by the carrier collection probability. We plot the carrier collection probability for the case of a surface trap density of \(S = 5E + 13\ \text{cm}^{-2}\) as Fig. 4e. As before, the carrier collection rate (for \(S = 5E + 13\ \text{cm}^{-2}\)) is found (Fig. 4f). Comparison of Fig. 4d and 4f reveals a strong dependence of carrier
collection rate on surface trap density. The peak carrier collection rate for $S = 1E + 12 \text{ cm}^{-2}$ is 2.45 times lower than optical generation rate. A further reduction by an order of magnitude (17 times) is observed as the trap density is increased to $S = 5E + 13 \text{ cm}^{-2}$. The above results directly follow from the plots of carrier collection probability (Fig. 4c and 4e). We see that the collection region narrows in the radial direction and shortens in the axial direction as the surface trap density increases. The peak carrier collection probability is unity for $S = 1E + 12 \text{ cm}^{-2}$ and drops to 0.28 for $S = 5E + 13 \text{ cm}^{-2}$. A majority of collected carriers are generated in space charge region close to the highly doped p+ region near the base of the NW. This phenomenon is discussed further in Supporting Information. The simulations confirm the important role of surface recombination in determining the region of carrier collection.

To see the influence of surface trap density on EQE, we simulate EQE spectra for three surface trap densities (Fig. 5). For an interface trap density of $S = 1E + 12 \text{ cm}^{-2}$, the EQE spectra of the four NW diameters (Fig. 5a) are similar to the absorption efficiency spectra (Fig 3c), but with the EQE magnitudes being smaller than absorption efficiency. As the interface trap density is increased, further reduction of the peak value of EQE occurs. The peaks in the EQE spectra also become narrower. We interpret the narrowing as arising from the interplay between the spatial distributions of the optical generation rate (e.g. Fig. 4b) and the carrier collection probability (e.g. Fig. 4e). As the illumination wavelength is varied, the optical generation spatial distribution changes. At high surface trap densities, the carrier collection region becomes progressively smaller. Thus the total carrier collection rate, obtained by integrating the product of the optical generation rate and carrier collection probability over the NW volume, becomes increasingly sensitive to the illumination wavelength. This behaviour leads to narrowing of the peaks for
\[ S = 5E + 12 \text{ cm}^{-2} \text{ (Fig. 5b)} \text{ and } S = 5E + 13 \text{ cm}^{-2} \text{ (Fig. 5c)} \]. It can also be seen that the peak value of EQE is significantly modified, with the peak EQE being \( \sim 0.04 \) for \( S = 5E + 13 \text{ cm}^{-2} \).

By comparing the measured (Fig. 3a) and simulated (Fig. 3d & Fig. 5) EQE spectra, we furthermore estimate the surface trap density to be \( S \approx 1E + 13 \text{ cm}^{-2} \).

In conclusion, we report the Ge NWs as narrowband photodetectors for the first time to the best of our knowledge. We anticipate that the fact that the spectral response is very narrow (FWHM down to 40 nm) and can be tuned in a wide range from visible (\( \sim 600 \text{ nm} \)) to SWIR wavelengths (\( \sim 1600 \text{ nm} \)) will be useful for applications such as multispectral imaging because input filtering is not needed. We further show that it is an interplay between optical and electrical properties that lead to the dramatic narrowing of spectral response that our devices exhibit. Lastly, we note that our methodology is generic and could be employed in other spectral regions using materials with the appropriate bandgaps.
Methods

Sample fabrication

The starting substrate for our device is a Ge wafer that is degenerately-doped p+. Intrinsic and n+ doped layers are grown epitaxially on this wafer to thicknesses of 1.5 µm and 300 nm, respectively, by L-NESS Lab, Italy. The wafer is cleaned in acetone and isopropyl alcohol (IPA). We spin coat the wafer with a PMMA bilayer (495-A2 and 950-A2). Electron beam lithography is performed (Elionix EL-125) at a beam current of 1 nA and dose of 1250 µC/cm² to pattern disks in nine different devices. Each device comprises a square array (period 1 µm) of disks of a certain diameter and has an overall extent of 100 × 100 µm. The disk diameters range from 50 to 250 nm, in steps of 25 nm. The wafer is developed for 90 seconds in a mixture of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA) in a ratio of 1:3 (MIBK:IPA). The wafer is then rinsed for 45 seconds in IPA. Aluminum (Al) is evaporated to a thickness of 60 nm, and the lift-off process is performed in acetone. In this way, we obtain samples containing arrays of Al disks (60 nm thick). This Al pattern is used as the mask for inductively coupled reactive ion etching (ICP RIE) of Ge in an SF₆/C₄F₈ based plasma. The etching is performed with SF₆ and C₄F₈ gases at flow rates of 42 sccm and 150-170 sccm, respectively, at a pressure of 10 mT and a temperature of 20 °C. We experiment with the flow rate of C₄F₈ to make the etching process anisotropic. The etch time is chosen with the goal of the NWs having heights of 2 µm. This height is selected with the goal of forming a n-i-p photodiode in the NW. Characterization data on the growth stack is provided in the Supporting Information. The Al remaining on the NW tips after etching is dissolved in Microposit MF CD-26 developer by immersion for five minutes. We next form a layer of Al₂O₃ (6 nm thick) on the sample by atomic layer deposition. The NW arrays are then completely embedded in PMMA (495-A8) by four cycles of spin coating (at 3000
rpm). After each spin coating step, the sample is heated to 180°C for two minutes. To expose the NW tips, oxygen plasma etching is performed. After each oxygen plasma etching step, the sample is imaged by atomic force microscopy (AFM). The etching and AFM imaging steps are performed until the NWs protrude by ~200 nm from the PMMA surface. The sample is then immersed in hydrofluoric acid (HF, diluted to 1%) to remove the Al₂O₃ from the exposed NW tips. At this point in the fabrication sequence, the sample consists of Ge NWs embedded in PMMA, with the n+ regions stripped of their Al₂O₃ coating and protruding from the PMMA. We next remove the PMMA by immersing the sample in acetone. A new PMMA layer is then spin coated with a thickness of 200 nm. The PMMA layer embeds the p+ doped base of the NW, ensuring electrical isolation. An oxygen plasma etch is carried out to remove the PMMA from the sidewalls of the intrinsic and n+ sections of the NW. Indium tin oxide (ITO) is then sputtered onto the sample, making direct contact with the top n+ section of the NW. As discussed earlier, all nine NW devices are electrically connected in parallel through their common top (ITO layer) and bottom (substrate) contacts. Illumination of the devices one-at-a-time allows them to be characterized separately. To increase the conductivity of the top (ITO) contact, gold (Au) is evaporated to a thickness of 30 nm. The NWs with diameters of 50 nm are fragile and collapse in the steps after the ICP-RIE. We therefore present results for eight arrays, whose NW nominal diameters range from 75 nm to 250 nm.

**Electrical Characterization**

We mount the sample on an Al pad of a printed circuit board (PCB) with high conductivity silver paste. In this way, the highly-doped substrate acts as the back contact. An electrical
connection is made to the top contact (Au layer on the device) using Au bonding wires and silver paste.

For current-voltage (I-V) measurements, the sample is removed from the PCB and mounted under a probe station, and I-V scans are performed using an Agilent 4156c semiconductor parameter analyzer.

**Optical characterization of fabricated devices**

We perform optical characterisation of our Ge NW devices using a homemade setup. Light from a Xe lamp (75 W total power) is focused onto the input slit of a monochromator that is equipped with two gratings appropriate for coverage of the visible-to-near IR ($\lambda = 400 – 1000 \text{ nm}$) and NIR to SWIR ($\lambda = 1000 – 1700 \text{ nm}$) wavelength ranges. The light emerging from the monochromator has a narrow bandwidth and can be tuned from $\lambda = 400 \text{ nm}$ to $1700 \text{ nm}$ by rotation of the grating. When the monochromator is set for an emission wavelength exceeding 1000 nm, a long pass filter (passing wavelengths above $1000 \text{ nm}$) is placed in the beam path to block the shorter wavelengths that are diffracted from the grating in the second diffraction order. A pinhole (diameter $\sim 500 \mu m$) is placed at the exit slit of the monochromator. The light emerging from this pinhole is chopped (at 85 Hz) and focused onto the sample with a microscope objective lens (Mitutoyo, nominal magnification $10 \times$). In this way, a focused spot (diameter $\sim 80 \mu m$) is formed. The sample is mounted on a translation stage, to enable the focused spot to be centred on each NW array device. The set-up also contains a beam-splitter and a CMOS camera, to facilitate alignment of the focused spot onto each NW device. The sample (mounted on the PCB) is connected to a lock-in amplifier whose reference is from the chopper, enabling the photocurrent to be measured as a function of illumination wavelength. The optical
power impinging upon the device at each wavelength is measured using calibrated Si and InGaAs photodetectors for the wavelength ranges of $\lambda = 400 - 900 \, nm$ and $\lambda = 900 - 1700 \, nm$, respectively. The responsivities ($R_\lambda$, units $A/W$) of our Ge NW devices are then found by dividing the photocurrent (units $A$) by the incident optical power (units $W$). The external quantum efficiency (EQE) is then found by $EQE = (R_\lambda \times hc/\lambda)/e$ where $R_\lambda$ is wavelength-dependent responsivity, $h$ is Planck’s constant, $c$ is the speed of light, $\lambda$ is the wavelength and $e$ is the elementary charge.

**Optical Simulations**

To model the optical response of our devices, three-dimensional simulations are performed using the finite difference time domain method with a commercial software package (FDTD Solutions from Lumerical). The dimensions of the Ge NWs used in the simulations are based on scanning electron microscope (SEM) images of fabricated devices. The refractive indices of ITO and PMMA used in the simulations are based on the results of ellipsometry. Illumination is provided by a plane wave at normal incidence. Periodic boundary conditions are used at the $x$– and $y$– boundaries of the simulation domain. Perfectly matched layers are used at the $z$– boundaries of the domain. In this way, simulations are performed on one unit cell ($1 \, \mu m \times 1 \, \mu m$) of the device. In finding the absorption efficiency, only the light absorbed within the part of the NW corresponding to the intrinsic region is taken into account. In the Supporting Information document, we provide the simulated profiles of various NW modes. These are found using a commercial software package (Mode Solutions from Lumerical).
Electrical modeling of the NW devices is performed using a commercial finite element modeling package (COMSOL Multiphysics). We perform carrier transport simulations to determine the collection probability as a function of position over a cross section through the NW. This collection probability map is then combined with the optical generation rate map (from the FDTD modeling) to yield a collection rate map over the NW. Integrating this quantum efficiency map over the NW at each wavelength gives the final EQE spectrum for that particular NW. Assumptions made by our method include the following: a) the perturbation of electric field by optical generation is assumed to be negligible, which is valid in low carrier injection cases in general and b) the density of surface recombination centers is uniform on the nanowires, independent of position and doping profile. A more detailed description of the method is provided in Supporting Information.
ASSOCIATED CONTENT

Supporting Information. Fabrication Scheme; Characterization of Ge growth stack; Light absorption in vertical nanowires; Ideality factor from I-V plots; Model for calculating carrier collection probability; Collection probability vs Surface trap density; Simulated absorption efficiency vs wavelength for nanowires of various diameters; Complete set of calculated EQE data. This material is available free of charge via the Internet at http://pubs.acs.org.
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Author Contributions

A.S. and K.B.C. conceived and designed the research study. A.S performed the experiments, analyzed the data and performed optical simulations. S.L. performed the electrical simulations. A.S., S.L., H.P. and K.B.C wrote the manuscript.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENT

The research was sponsored in part by the Army Research Laboratory and was accomplished under Cooperative Agreement Number W911NF-13-2-0015. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U.S. Government. The US Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein. The research was sponsored in part by the National Science Foundation (NSF, Grant No. ECCS-130756). Fabrication work was performed at the Harvard Center for Nanoscale Systems (CNS), which was supported by the NSF. S.L. and K.B.C. acknowledge support from the Australian Research Council (DP150103736 and FT140100577) and from the Victorian Endowment for Science, Knowledge and Innovation (VESKI).
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Figure 1. Germanium nanowire (Ge NW) photodetector devices. (a) Scanning electron micrographs (SEMs) of Ge NW arrays after (i) etching and (ii) after deposition of ITO/Au contact. (iii). Bright-field optical microscope image of completed NW devices, with labels “1”-“9” added to denote NW diameters of 50 – 250 nm (steps of 25 nm). SEMs of NWs with diameters of (iv) 75 nm and (v) 125 nm. (vi) Close up on 175nm diameter NW array. (b).
Schematic illustration of completed device. Scale bars are 100 µm for (i)-(iii), 1 µm for (iv)-(v) and 400 nm for (vi).

**Figure 2.** Characterization of Ge NW photodetectors (a) Photographs of Ge NW photodetector device mounted on PCB. Inset: a close-up image of the device, with Au wires and Ag paste used for connections to top and bottom contacts. (b) Schematic of optical characterisation set-up. (c) Current-voltage (I-V) characteristics measured on fabricated devices in light and dark conditions. Inset: enlarged view of I-V characteristic for reverse bias. (d) I-V characteristics plotted in log-linear scale. (e) Current vs. time for Ge NW device, measured under zero bias with illumination switched "on" and "off".
Figure 3. Ge NW photodetectors: simulations and experiments. (a) Simulated absorption efficiency vs. wavelength for arrays of Ge NWs with a range of diameters on a Ge substrate. (b) Experimentally-measured EQE vs. wavelength of Ge NW devices with a range of diameters. (c) Simulated absorption efficiency vs. wavelength for Ge NW structures whose geometries are chosen to match those of fabricated devices. Unlike panel a), simulation includes all materials in the device (e.g. ITO, Au, PMMA, Al₂O₃) and not just Ge. (d) Simulated EQE vs. wavelength,
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Figure 5. EQE vs. wavelength for several trap densities, as found by combining optical and electrical simulations (a) Simulated EQE vs. wavelength for surface trap density $S = 1E + 12 \text{ cm}^{-2}$. (b) Simulated EQE with surface trap density $S = 5E + 12 \text{ cm}^{-2}$. (c) Simulated EQE with surface trap density $S = 5E + 13 \text{ cm}^{-2}$. See Fig. 3d. for Simulated EQE with surface trap density $S = 1E + 13 \text{ cm}^{-2}$ . Further details are provided in Supporting Information.
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