Silicon p-i-n Junction Fibers

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Conventional wafer-based microelectronics are typically fabricated on a length scale of millimeters to centimeters on rigid substrates. Extending electronic function to longer length scales and more flexible forms[1] has long been of interest for a wide range of application areas such as power generation,[2] chemical sensing,[3] foldable displays,[4,5] and biomedical devices (e.g., epidermal electronics).[6–8] 1D fibers are now emerging as flexible structures[9–11] that can allow electronic function to be exploited over length scales from meters[10] to even kilometers[12] and can also be configured into large 2D woven structures and 2D and 3D arrays.[13] These fibers are further extending the scope of the field to applications such as 3D photodetectors,[13] imaging fabrics,[13] and telecommunications,[14] with many more applications possible with further improvements in electronic fiber device performance.

Two approaches to electronic fibers have emerged, one based on high-temperature drawing[9,11] and another based on high-pressure chemical vapor deposition (HPCVD)[10] (Figure 1 and Supporting Information, Figure S1). To fabricate semiconductor fiber materials via drawing, a macroscale preform with an appropriate semiconductor inside is heated and drawn down to smaller dimensions. To fabricate semiconductor fiber materials via HPCVD, a high-pressure precursor is configured to flow down a nanoscale to microscale pore or array of pores in a glass fiber, which is then heated to induce deposition. Combinations of semiconductors, insulators, and metals that are assembled into a preform and drawn must be chosen to have an appropriate match of melting points and viscosities. Furthermore, they must not react with each other in an undesired way at high temperature.[11,13] At least one of the preform materials must have a viscosity suitable for drawing. Such materials are usually amorphous in solid form; materials that are crystalline in solid form usually have melt viscosities too low for drawing.

The material suitable for drawing may serve as a cladding to contain low-melt-viscosity metals or semiconductors. Post-drawing processing, such as annealing to induce crystallization or chemical reactions, can further extend the range of drawn fiber materials.[16] Although silicon and germanium can be drawn into solid wires by embedding them in silica,[13] their melt viscosities may be too low to allow for the formation of precise, sharply defined layers and interfaces in fibers. Migration of oxygen from the silica cladding glass into the semiconductor core and any interfaces in it is another issue that has been addressed by approaches such as gettering. It becomes more difficult to avoid as the draw temperature is raised.

The difficulties in fabricating layers and in some cases even wires are more severe for semiconductors that have high melting points, melt incongruently, and/or have appreciable vapor pressures when molten. Many technologically useful compound semiconductors (e.g., zinc selenide, gallium arsenide),[15] for example, contain a volatile pnictide or chalcogenide element and/or have high lattice energies. Volatile elements may leave the semiconductor core during drawing and/or distort the cladding glass. The drawing process thus faces significant limitations in fabricating structures such as precisely defined layers composed of the crystalline unary and compound semiconductors employed for modern electronics and optoelectronics. However, HPCVD has been shown to allow for deposition in single capillary pores, as well as precisely engineered pore arrays to form sharply defined layers (and wires) of unary semiconductors, such as crystalline silicon and germanium,[10] and compound semiconductors such as zinc selenide.[15] By exploiting the broad knowledge base developed for CVD on conventional planar substrates, it will be possible to deposit layers and wires of most, if not all, of the technologically relevant semiconductors in fiber pores.

As for junctions formed in conventional wafer-based microelectronics and photonics, the ability to fabricate thin films is critical to electronic fiber junctions. Doped semiconductor junctions that have built-in electric potential enable a wide range of desirable optoelectronic functions,[18] such as high speed and sensitive, low-noise photodetection, photovoltaic power generation, and efficient light emission. Photodiode behavior that arises upon annealing drawn amorphous chalcogenide fibers has been reported,[16] but such structures are not expected to have the performance of diodes fabricated from precisely doped single phase crystalline silicon or crystalline compound semiconductors that are more readily fabricated by HPCVD. Crystalline materials in general have higher carrier mobilities and enable better device performance than mixed phase crystalline/amorphous materials. The photovoltaic efficiency and photoresponse bandwidth of the drawn fibers has not been reported.[16]
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Figure 1. Silicon p-i-n junction fibers fabricated in capillary templates via high-pressure chemical vapor deposition. a) Scanning electron micrograph (SEM) of a deposited and cleaved junction in-fiber structure. b) Differential interference contrast (DIC) optical micrograph of a representative 15 μm diameter Si p-i-n junction. The p⁺ and n⁻ layers were selectively etched in a HF-HNO₃-CH₃COOH (1:3:8 by volume) solution for 3 s to reveal the doping boundaries. DIC is sensitive to the nanoscale height differences arising from the dopant selective etching. c) A junction fiber within a ~1 m long silica template wrapped into a coil. d) A 6 μm diameter silicon junction-fiber core etched out of its silica cladding can be manipulated into a tight knot. e) Raman spectra collected from the different doped regions of a Si p-i-n junction. The spectra are fit to the Fano resonance curve I(ω) = I₀(q²/2 + a - a₀)²/[(a - a₀)² + (Γ/2)²], where I₀ is the photon intensity, a is the Raman shift, and a₀, Γ, and q are the parameters associated with the peak position, width, and profile asymmetry, respectively. In particular, q⁻¹ scales with doping concentration and is positive for p-type Si, negative for n-Si, and 0 for i-Si (the small, negative q⁻¹ for i-Si shown here is more likely due to its polycrystalline nature rather than its slight n-type intrinsic doping). f) Abrupt junction profile revealed by sharp changes of q⁻¹ within a distance of 200 nm (the microscopy scanning resolution) or less at the n⁺-i and i-p⁻ interfaces.

Here, we report silicon p-i-n photodiode junction fibers fabricated via HPCVD. We previously reported waveguiding metallic silicon Schottky junction fibers fabricated by HPCVD that have gigahertz bandwidth. However, p-i-n photodiode junctions typically have higher quantum efficiency than Schottky photodiodes, a desirable characteristic for both photodetector and photovoltaic applications. We demonstrate that these p-i-n photodiode junction fibers function as optoelectronic devices, such as solar power wires and high speed (1.8 GHz) photodetectors. They also exhibit interesting waveguide behavior, with the potential for enabling advanced light-management schemes for high-efficiency photovoltaic conversion and optoelectronic detection. Finally, we show that silicon layers can be deposited over lengths of more than 10 m in fiber pores, demonstrating the potential for scaling the p-i-n junctions reported here to much longer lengths.

To make silicon junction fibers with doped p and n layers by HPCVD, it was first necessary to investigate the high-pressure dopant chemistry of the relevant hydride precursors. Silane (SiH₄) mixed with diborane (B₂H₆) was chosen for deposition of p-type Si and SiH₄ with phosphine (PH₃) for n-type Si. The dopant concentration, ranging from 10¹⁶ to 10²⁰ cm⁻³, was controlled by varying the molar ratio of the precursors. At 400 °C, the deposition rate is <1 nm min⁻¹ for intrinsic Si (i-Si) but increases dramatically to ~300 nm min⁻¹ when ~1 at% B₂H₆ is added. A similar trend is observed for conventional CVD and is thought to be due to a boron catalytic effect. Adding ~1% PH₃ to the high-pressure reaction mixture also increases the deposition rate, although to a lesser degree (e.g., at 500 °C, intrinsic Si deposits at 6–10 nm min⁻¹, while phosphorus doped Si deposits at 15–20 nm min⁻¹). This trend is opposite to that observed for conventional CVD, for which there is a decrease in rate thought to be associated with blockage of surface adsorption by phosphorus species. At high pressure, the concentration of intermediates (e.g., SiH₂, SiH₃PH₂) produced from homogeneous gas phase reactions of SiH₄ and/or PH₃ should increase because of changes in both reaction rate constants and the much higher precursor concentrations; these reactive intermediates are known to compete effectively with the phosphorus species for adsorption sites and could therefore increase the deposition rate. While increased deposition rates are, in general beneficial in allowing for reduced processing cost, the reaction conditions had to be tailored to accommodate the high-pressure reaction kinetics for different dopants. Taking the variations in chemistry into account, the conditions were optimized to allow for the deposition of annular films with controlled dopant and thickness profiles. For example, to realize uniform-thickness phosphorus-doped Si layers over a length of 1 m, a deposition temperature of 525 °C was used so that the precursor conversion efficiency was ~1.5 at% per meter, precluding rapid depletion of precursor along this length.
The as-deposited amorphous films are subsequently annealed at high temperatures to crystallize the materials and activate the dopants. The Si fibers are polycrystalline,[10] as revealed by transmission electron microscopy images (Supporting Information, Figure S2). Effective doping is evidenced by field-effect-transistor measurements performed on 1 cm-long Si tubes in fiber pores (Supporting Information, Figure S3). The electrical-transfer characteristics show $p$ or $n$ type behavior for boron or phosphorous doped Si, respectively, with the carrier mobility measured as $\approx30 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for electrons and $\approx2 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for holes, comparable to the mobilities of polycrystalline Si films made by conventional CVD.[19]

Coaxial $p$-$i$-$n$ structured fibers were formed by depositing $n^+$, $i$, and $p^+$ layers of amorphous Si in sequence in 5–15 $\mu$m diameter pores, up to 1.5 m long, followed by crystallization (Figure 1a,b). It was important to minimize the mechanical strain caused by thermal-expansion mismatches between materials by an appropriate choice of thermal-processing conditions (see Experimental Section). It was furthermore necessary to avoid mechanical strain that could be caused by volume shrinkage upon evolution of hydrogen that was incorporated into the amorphous semiconductor film and then released upon crystallization; this strain was avoided by choosing processing conditions that do not allow for much hydrogen incorporation into the amorphous films. The $p^+$ and $n^+$ layers were both heavily doped to concentrations of $\approx 10^{20} \text{ cm}^{-3}$, as estimated from the partial pressure of the dopant precursor in reactant mixtures. The $i$ layer was not intentionally doped but was slightly $n$ type, with a free electron concentration of $\approx 10^{16} \text{ cm}^{-3}$ as determined by field-effect-transistor measurements (thus the junctions made here, strictly speaking, are $p^+$$n^-$$n^+$). However, we refer to them as $p$-$i$-$n$). Complete filling of the pores with the innermost layer is possible because the hydrogen reaction byproduct can diffuse through the silica capillary walls (Figure 1b).[20]

The Si $p$-$i$-$n$ wires can be employed inside the mechanically robust silica capillary template (Figure 1c) or be etched out (Figure 1d). When etched out, they are flexible and strong, despite their polycrystalline nature. They can easily be manipulated into knotted loops; the strain they can sustain is estimated to be $\approx 1\%$ from the ratio of their diameters to the bending loop diameters (Figure 1d). The doped layer structure is revealed by micro-Raman spectroscopy; there are abrupt $n^+$$i$ and $i$$p^+$ interfaces (Figure 1e,f). We note that annealing at elevated temperature for an extended period (e.g., $950^\circ\text{C}, 12$ h) can cause significant dopant interdiffusion that is avoided by a judicious choice of junction fabrication scheme (Supporting Information, Figure S4).

The $p$-$i$-$n$ fibers behave as smart fibers with active photovoltaic and optoelectronic function. A 1 cm-long section of $p$-$i$-$n$ fiber exhibits the defining characteristic of a junction diode, a rectifying current–voltage ($I$–$V$) curve (Figure 2). Electrode contacting was performed by wet chemical etching to expose the $n$ layer on one end of the junction and the $p^+$ core on the opposite end, followed by evaporation of nickel on these exposed surfaces. The ideality factor for a 6 $\mu$m diameter sample was determined to be 1.7 by exponentially fitting the dark $I$–$V$ curve in the $0.1$–$0.3$ V range; in comparison, a value of 1.96 has been reported for coaxial Si nanowire $p$-$i$-$n$ junctions[21] and 1.85 for single crystalline membrane Si $p$$p$-$n$$n$ junction solar cells (1 is expected for an ideal junction).[22] The photovoltaic response of the fiber junctions was evaluated with simulated air mass 1.5 (AM 1.5) solar illumination; the open-circuit voltage ($V_{oc}$), short-circuit current density, and fill factor were measured to be 0.22 V, 2 mA cm$^{-2}$, and 0.55 respectively, resulting in an overall conversion efficiency of 0.5%. One reason for the low efficiency is low light absorption due to the non-optimal thicknesses of the doped and intrinsic layers in the junctions presented here. Taking the sample shown in Figure 3 as an example, the outermost 0.5 $\mu$m $n^+$ layer substantially absorbs short-wavelength

![Figure 2](https://www.materialsviews.com/doi/abs/10.1002/adma.201203879)  
**Figure 2.** Si junction photovoltaic and photodetecting fibers. The $n^+$ and $p^+$ layers are contacted by removal of the silica cladding via selective etching at the two fiber ends, followed by Ti and Au evaporation. In-Ga eutectic is then placed over to make contacts. The inset shows the device at one end. Simulated AM 1.5 illumination is used to evaluate the solar-cell performance, while a 633 nm laser demonstrates the photodetection capability. Illumination is from the side. This junction has a 0.5 $\mu$m-thick $n^+$ layer, a 1 $\mu$m-thick $i$ layer, and a 3 $\mu$m-diameter $p^+$ core.

![Figure 3](https://www.materialsviews.com/doi/abs/10.1002/adma.201203879)  
**Figure 3.** High-speed photodetection with Si junction fibers. The inset shows the schematic of experimental setup. 10 ps pulsed 633 nm light impinges on the junction from the side; negative bias voltage is applied via a bias tee and the photoresponse is measured using an oscilloscope. This junction has a 100 nm-thick $n^+$ layer (to minimize the diffusion current), a 3 $\mu$m-thick $i$ layer, and an 8 $\mu$m-diameter $p^+$ core.
light, but most of the energy will be wasted as heat since the minority-carrier diffusion length is short (<100 nm as a rough estimation) due to the $2 \times 10^{20}$ cm$^{-3}$ high doping level and the poly-crystalline structure. The 1 μm i layer, on the other hand, is not thick enough to efficiently absorb long-wavelength light for photovoltaic conversion. A roughly 5-fold reduction is estimated in overall light absorption integrated over wavelengths of 400–1100 nm, as compared with conventional 200 μm-thick planar Si p-i-n junction solar cells (Supporting Information, Figure S5). This difficulty could be overcome by making junctions with thinner $n^\ast$ layers and thicker i layers, and/or by the light management approaches discussed below. Improvement in efficiency is also expected as the material quality is further improved. For example, crystalline domains many tens of microns long that approximate single crystal behavior may be realized by means of appropriate crystallization schemes. The 1D fiber geometry is well suited for propagating crystal growth over long distances.

Fiber-based solar cells have been receiving increasing attention owing to their potential for use in lightweight, flexible configurations such as textiles, which can be portable, foldable, and even wearable. Their round cross-sections and freestanding nature also allow for absorption of light that is incident from all directions, thereby enabling powerful harvesting from diffuse and reflected light, similar to the approach that has been demonstrated with cylindrical-film solar cells and spherical Si solar cells. In contrast, conventional planar solar cells on rigid substrates can only harvest light from one side. Arrays of fibers could also be configured that increase collection efficiency by allowing a given fiber to harvest light scattered and/or reflected off of neighboring fibers and also neighboring planar or curved reflectors. The effort to date on fiber solar cells has been largely focused on organic and polymer materials, but the high natural abundance of Si and the excellent reliability of Si devices, their ease of fabrication, and their potentially high performance make Si fiber solar cells attractive. We note that to fully exploit meters-long fiber p-i-n junctions, it will be necessary to develop long, parallel in-fiber wire electrodes configured to reduce the series resistance. Such a contacting scheme would also permit high-speed electronic function to be extended to meters-long fiber devices, and fiber solar cells. Fabrication of suitable metal electrodes via HPCVD is possible.

The crystalline Si junction structures also allow the fibers to function as high performance optoelectronic devices, a merit generally not shared by organic or non-crystalline optoelectronics. The photodetection responsivity is demonstrated to be $0.3$ A W$^{-1}$ at 633 nm wavelength for the junction under zero or negative bias (Figure 2), significantly higher than reported for a fiber photodetector based on a Pt-Si Schottky diode. The large built-in electric field in the i-layer quickly sweeps out photoexcited carriers, allowing for fast photodetection. A 15 μm diameter junction fiber with a 100 nm thick $n^\ast$ layer exhibits a 3 dB bandwidth of 1.8 GHz (Figure 3) when illuminated over a length of approximately 1 mm (the resulting capacitance is on the order of 1 pF), a speed similar to the Schottky fiber detector. Specifically, an electric pulse with a 115 ps rise time and a 180 ps fall time is observed as the response to a 10 ps 633 nm laser pulse impinging on the side of the junction with a reverse-bias voltage $V_{bias}$ of $–3.5$ V. We note that commercially available Si p-i-n planar photodiodes typically have bandwidths ranging from 10 MHz to 10 GHz. Fibers made of chalcogenide glasses have shown a photodetection capability based on a simple photoconductive effect, but no speed has been reported. Furthermore, these chalcogenide photoconducting fibers have been used to demonstrate 3D photodetectors that can determine the direction of an incoming light beam. We expect extended silicon junction fibers could replicate this function but with higher speed and sensitivity.

The waveguiding aspects of fiber devices open new functionalities because light and materials can interact over distances that are not possible in conventional non-waveguiding structures. We find that light can be guided in the i-layer of the junctions (Figure 4a and Supporting Information, Figure S6). Cross-sectional intensity profiles observed for 1550 nm light exiting the junction after being focused into the opposite end reveal an intensity profile characteristic of an HE$_{21}$ mode (Figure 4b,c). This waveguide behavior is possible because the refractive index of Si decreases upon doping due to the

Figure 4. Waveguide behavior of the Si p-i-n junction fibers. a) Diagram showing that light is guided in the i layer along the fiber length via total internal reflection, while carrier collection is in the cross-sectional direction. b) Experimentally observed intensity profile when 1550 nm light is launched onto the fiber end, which matches the calculated HE$_{21}$ mode profile (c) by finite element simulation using COMSOL. d) Waveguide photodetection at 1064 nm. e) Intensity modulation of 1550 nm light.
plasma-dispersion effect,[31] leading to total internal reflection at the $i$-$p^+$ and $i$-$n^+$ interfaces. From the estimated dopant concentrations and the measured free-carrier concentrations, a refractive-index difference between the $i$ layer and the heavily doped $p^+$ and $n^+$ layers of 0.1 can be estimated. This difference gives rise to a numerical aperture of about 0.83 and a large acceptance angle of 56° (i.e., light with an incidence angle $\theta$, less than 56° will be guided, Figure 4a). If the index difference were made larger than $\approx 0.15$ with even higher doping, an acceptance angle of 90° could be achieved. Then, light incident on the $i$ layer from above could all be guided into the junction. The overall transmission loss is measured to be on the order of $10 \, \text{dB mm}^{-1}$ at the wavelengths of 1300–1550 nm; a systematic study is needed to reveal the loss mechanisms and thereby reduce undesired losses.

Waveguide optoelectronic devices (Figure 4a) are advantageous compared with conventional normal-incidence junctions (Figure 3 inset), as not only can light effectively interact with materials over long distances to enhance device efficiency, but the carrier transport within the device can also be independently controlled in the orthogonal direction to maximize the device speed or allow for the use of lower quality materials with shorter carrier diffusion lengths.[32] Here, we show preliminary waveguide optoelectronic measurements with infrared light that is nearly transparent for Si. For example, $\approx 100 \, \text{MHz}$ waveguide photodetection is demonstrated at 1064 nm wavelength with a 15 $\mu$m diameter junction negatively biased (Figure 4d and Supporting Information, Figure S7). We chose 1064 nm light here because its photon energy is above the band gap of Si, but its absorption coefficient is low ($\approx 2 \, \text{mm-thick Si is required to absorb} \geq 90\% \text{ of 1064 nm light}$). The same junction can also be used to modulate the intensity of infrared light with energy below the Si bandgap. For example, with positive bias, injected free carriers in the $i$-layer can attenuate continuous wave (CW) 1550 nm waveguided light (Figure 4e). This waveguide behavior can also benefit applications in solar cells. Vertical arrays of Si micro/nanowire $p$-$n$ junctions are being intensively investigated for high-efficiency solar cells utilizing the orthogonal light absorption-carrier collection approach.[33–35] Waveguiding in $p$-$i$-$n$ junctions could further enhance this decoupling strategy as light absorption will preferentially occur in the $i$-region where carrier lifetimes are longer and a strong electric field exists. With large acceptance angles, diffuse sunlight can be collected, guided, and harvested. Meanwhile, the high conductivity of the doped layers will facilitate reducing the series resistance.

An attractive aspect of the drawing process is that it can economically produce kilometer lengths of semiconductor fiber,[12] although only with the aforementioned materials limitations.[35]

Conventional CVD reactors have not been scaled to very long lengths in view of the obvious difficulties with mass transport, space, etc. Deposition over long lengths can then only be achieved by repeated deposition steps as the substrate is translated (e.g., roll-to-roll processing on flexible 2D substrates), which is much more cumbersome and less economic than a one-step deposition process. However, employing the fiber capillary as its own microreactor[30] has the advantage that a very long length of fiber can be coiled and heated while filled with precursor, allowing for deposition of in-fiber layers in one simple step with a compact and very low-cost apparatus. The fiber capillary itself can be produced economically by the well-established fiber-drawing process. Thus, as a first step towards investigating the scalability of the HPCVD process, we show that it can be used to fabricate silicon layers in silica capillaries 10 m long and 15 $\mu$m in diameter (Figure 5, see Experimental Section). Optical inspection along the fiber reveals that deposition occurred along its entire length. Further development of the deposition processes for undoped Si and metals should allow for 10 m long or even longer $p$-$i$-$n$ contacted junctions. This $p$-$i$-$n$ fiber could be produced economically and its high performance exploited in a variety of woven and array applications.

Finally, we note that the approach reported here represents a general method for realizing $p$-$i$-$n$ junctions in confined geometries for which mass flow is restricted. Although capillary fibers are the focus of the present study, because HPCVD is fundamentally a templated approach, it can thus be adapted to two- or three-dimensional substrates, allowing for the fabrication of devices with complex architectures[37] such as junction array solar cells.

Experimental Section

Junction Deposition: High-pressure reservoirs were constructed using stainless-steel valves, fittings, and tubing (High Pressure Equipment Company). Mixtures of SiH$_4$, dopant precursor (B$_2$H$_6$ or PH$_3$) and He carrier gas were introduced into the reservoirs via cryogenic or high-pressure pumps, to a total pressure of $\approx 30 \, \text{MPa}$. Capillary fibers were directly connected to the reservoirs and placed in resistively heated furnaces for deposition. For fibers that were 10 cm to 1.5 m long, furnaces of corresponding lengths were used with the fibers passing straight through (Supporting Information, Figure S1). Heavily boron doped Si was deposited at 300 °C and intrinsic and phosphorus doped Si at 525 °C. The deposited amorphous Si was crystallized at 850–900 °C for 30 min.
10 m-Long Si Fiber Process: A 10 m length of capillary fiber was wrapped around an aluminum cylinder of 1.25 cm in diameter and placed in a tube furnace. Heavily boron-doped amorphous Si was deposited at a temperature of 150 °C. The catalytic effect of the boron and the high pressures enabled deposition at these low temperatures.

Materials Characterization: Raman spectroscopy images were obtained with a 200 nm resolution using a WITec alpha300 S microscope in its confocal Raman mode with 633 nm laser excitation. Transmission electron microscopy images were collected using a JEOL-2010 microscope.

Waveguide: 0.5–5 mm long fibers with junction devices inside were polished at their ends. Laser light was launched into the junctions via a 60x microscope objective lens (0.85 NA); an identical objective lens was placed at the output end to capture the transmitted light and focus it onto an infrared camera for imaging (Supporting Information, Figure S6).

Optoelectronic Devices and Measurements: For non-waveguiding fiber junction devices, electrode contacting on the n+ layers and p+ cores was performed by first etching away the silica in which they were embedded with hydrofluoric (HF) acid to expose n+ Si layers at both ends. p+ cores were further exposed at one end by time-controlled etching of Si with HF:HNO3 mixture. Ti and Au were then evaporated on these exposed Si surfaces to form contacts. For waveguide devices, the fiber ends were first polished, and 300 nm SiO2 was then sputtered on the polished ends. A focused-ion-beam (FIB) system (FEI Quanta 200 3D) was used to open contact windows for both n+ and p+ regions, with the sputtered SiO2 as the insulating barrier in between. Pt wires were deposited on n+ and p+ using the same FIB system to make contacts. Solar-cell measurements were performed using an I–V station and a Newport solar simulator. Photodetection was performed using a supercontinuum laser source (Fianium SC450) to obtain >10 ps light pulses at desired wavelengths. Light was coupled into the junction end using an objective lens as in the waveguide experiments (Supporting Information, Figure S6). The devices were connected via a bias tee to a sampling oscilloscope with a 20 GHz bandwidth and 50 Ω input impedance (Agilent Infinium 86100A with 86105A module).

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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