The realization of on-chip microspectrometers would allow spectroscopy and colorimetry measurement systems to be readily incorporated into platforms for which size and weight are critical, such as consumer grade electronics, smartphones, and unmanned aerial vehicles. This would allow them to find use in diverse fields such as interior design, agriculture, and in machine vision applications. All spectrometers require a detector or detector array and optical elements for spectral discrimination. A single device that combines both detection and spectral discrimination functions therefore represents an ultimate limit of miniaturization. Motivated by this, we here experimentally demonstrate a novel nanostructured silicon-based photodetector design whose responsivity can be tailored by an appropriate choice of geometric parameters. We utilize a unique doping profile with two vertically stacked, back-to-back photodiode regions, which allows us to double the number of detectors in a given on-chip footprint. By patterning the top photosensitive regions of each device with two sets of interleaved vertical slab waveguide arrays of varied width and period, we define the absorption spectra (and thus responsivity spectra) of both the upper and lower photodiode regions. We then use twenty such “fishnet pixels” to form a microspectrometer chip and demonstrate the reconstruction of four test spectra using a two-stage supervised machine-learning-based reconstruction algorithm.

1. INTRODUCTION

Recent efforts to miniaturize spectrometers have involved replacing the use of diffractive elements and beam propagation by ultrathin filter devices with tailored transmission spectra. The latter have included quantum dots (QDs) [1], thin films [2,3], and plasmonic resonators at visible [4,5] and infrared [6,7] wavelengths. In each of these devices, a number of distinct wavelength-filtering elements are coupled with either photodetector arrays such as a CCD camera or an external photodetector. The generated photocurrents at each pixel thus depend on the transmission of each filter element, the photodetector responsivity, and the incident spectrum. Knowledge of the transmission functions and detector responsivity can then be used to computationally estimate the incident spectrum based on the measured photocurrents. Drawbacks associated with these designs include the use of toxic or CMOS-incompatible materials such as cadmium [1] or noble metals [5–7] or the use of fabrication techniques that do not lend themselves to high-throughput wafer-scale manufacturing [1,4]. Furthermore, the materials comprising the spectral filters can introduce their own limitations to the microspectrometer operating range. For example, QD-based absorption filters on a silicon CCD matrix will only operate above the band gap of the constituent QDs, typically above 1.5 eV [1]. On the other hand, thin film bandpass filter arrays and plasmonic nanoantenna arrays both suffer from angle-dependent transmission functions [8] as well as the potential for stray light pixel cross-talk [9], which if unaccounted for can reduce the utility of a microspectrometer.

Previous work on etched nanowire photodetectors has sought to reduce these effects by combining the spectral filtering and photodetection functions into one all-nanophotonic device [10–12], which allows for the reduction in optical pixel crosstalk caused by stray light in filter-on-CCD/CMOS sensor architectures. The nanowires behave like cylindrical dielectric waveguides with electric field distributions and charge carrier generation rates determined by the wavelength of light and the radii of the nanowires. Further design improvements to nanowire-based photodetectors include reducing the on-chip footprint and total size of nanowire devices via a doping profile that forms two vertically stacked photodetector regions, where the top region is patterned into active nanowire photodetectors and the bottom region is a mesa detector passively filtered by the above nanowires [11]. However, perhaps due to the need to planarize the nanowire device to establish electrical contact to the tops of the nanowires,
due to efficiency issues arising from the large surface-area-to-volume ratio of nanowires and due to the nanowires being fragile because they are very thin, we have yet to see a nanowire-based device with the large number of detectors required for a microspectrometer. Here we introduce a nanophotonic detector design based on two sets of interleaved vertically oriented dielectric slab waveguide arrays (WGA), termed the “fishnet.” Here the conceptual similarity with vertical nanowire devices is clear, with the cylindrical waveguides being replaced with interconnected slab waveguides. The interconnected nature of the fishnet design allows us to forgo troublesome planarization involving precise deposition and etch-back steps [11], and it provides improved mechanical robustness compared with nanowire designs as well as an extra degree of freedom (the array period) to tailor each detector’s responsivity spectrum.

2. DESIGN AND EXPERIMENTAL METHODS

Figures 1(a) and 1(b) depict the design concept of our fishnet pixels, including a schematic cross section. Each fishnet photodetector comprises interleaved orthogonal sets of vertically oriented silicon slab waveguides etched into a multilayer doped silicon substrate. The fishnet waveguides are etched from the substrate surface down to an embedded $n^+$ layer, defining the top photodetector. The waveguides comprising the fishnet region are oriented out of the plane of the substrate, allowing direct coupling of incoming light to the silicon nanostructures and thereby foregoing the need for momentum matching with on-chip couplers such as gratings or prisms [13]. The array period and waveguide widths of each fishnet pixel are determined in the lithography step of the fabrication process and thereby enable control over its optical absorption. To electrically isolate the fishnet detectors from one another, a mesa is etched from the embedded $n^+$ layer to the bottom $p^+$ layer below each fishnet. Each mesa is also a photodetector.

Figure 1(b) also indicates the thicknesses of the doped silicon layers. These were epitaxially grown (layer-by-layer) on degenerately doped $p + 4''$ Si substrates by the IQE company. Initially, 4 μm of lightly $n$-doped silicon ($2 \times 10^{16}$ atoms/cm$^3$) was grown, followed by a 1 μm $n$ + layer ($6 \times 10^{18}$ atoms/cm$^3$), which thereby forms the first $p - i - n$ junction, which will act as the mesa detector. Another 2 μm of $n$-Si was grown and capped with a 200 nm layer of $p +$ Si, forming the second $p - i - n$ junction that will form the fishnet photodiode region. We added electrical contacts to the bottom $p^+$ substrate and the top $p^+$ layer to bias the structure and to form two counter-facing PIN photodiodes. In the absence of light, the current through this device under forward bias (top electrode positively biased with respect to the bottom electrode) should only be equal to the dark (reverse bias) current of the bottom (mesa) photodiode. When the entire device is reverse biased, however (top electrode negatively biased with respect to the bottom electrode), the current is equal to the dark current of the top diode.

To fabricate the 23 fishnet pixels comprising our microspectrometer chip, standard silicon processes were used. First, an Al etch mask (65 nm thick) was created via lift-off using electron beam lithography (100 kV Vistec EPBG5000+) and electron beam evaporation (IntVAC NanoChrome II). Inductively coupled plasma reactive ion etching (ICP-RIE, Oxford Instruments PlasmaLab 100) was used to create the Si nanostructures comprising each fishnet detector. Here 40 sccm of $SF_6$ and 90 sccm of $Cl_2F_8$ were used in a carefully calibrated pseudo-Bosch etch recipe to create silicon nanostructures with smooth, vertical sidewalls with an aspect ratio greater than 30. Each fishnet detector region must to be etched to a depth greater than 2.2 μm to ensure the intrinsic region of each upper $p - i - n$ junction is fully patterned. Failure to etch through the top intrinsic region would result in large contributions to the photocurrent from light absorbed in the remaining unpatterned intrinsic silicon. This fishnet design is also amenable to fabrication via metal-assisted chemical etching as an alternative to ICP-RIE [14]. After etching, the Al mask was chemically removed (Transene Al etchant) and the photore sist (AZ4562) was spin-coated to a thickness of 8 μm. Direct-write UV lithography (IMP SF100) was used to define an etch mask for the mesa etching step, protecting both the fishnet and pad regions of each pixel. Mesas with thickness of 5.5 μm were then etched using the same ICP-RIE tool. Direct-write UV lithography and evaporation were again used to define a lift-off mask for the final metallization step in which Al pads (200 nm thick) were added to the pad mesa of each pixel. Finally, the silicon die was mounted and wire-bonded (FS BondTec, 20 μm AlSi wire) in a ceramic
DIP-24 chip carrier, with one pin bonded to a common contact on the substrate $p^+$ layer.

Electrical characterization of the photodetector devices was carried out using a picoammeter (Keithley 6485). To measure the responsivity of each detector, its photocurrent in response to illumination by monochromatic light of a known wavelength and power was recorded. The illumination was provided by a laser-driven light source (Energetiq EQ-99X) filtered by a monochromator (Princeton Instruments Acton SP2150) and focused onto each device with a microscope objective (Nikon LU Plan Fluor, 0.30 NA, 10×). The wavelength range of the measurements was 400 to 1000 nm in steps of 5 nm. At each wavelength, the photocurrent from the fishnet photodiode was measured by supplying a bias to the top electrode of $-1.0\,\text{V}$. Similarly, the photocurrent from the mesa photodiode was measured by biasing the device at $+1.0\,\text{V}$.

After measuring the responsivities of each fishnet and mesa detector, it is possible to use the device to reconstruct unknown spectra. To demonstrate this, a white LED lamp (Thorlabs MCWHLP1) was used to illuminate the entire chip, and the photocurrents from each pixel, generated with $+1\,\text{V}$ and $-1\,\text{V}$ bias, were recorded. These measured photocurrents were then combined with the known detector responsivities to reconstruct an estimate of the unknown spectrum. Here we used a two-stage reconstruction method. The first stage employed a modified Tikhonov regularization method (also known as weight decay or ridge regression) [5], which allows us to solve this ill-conditioned inverse problem. The output from this calculation was then refined using a simulated annealing algorithm to improve the final reconstructed spectrum [15]. Simulated annealing can be used with any initial guess spectrum; however, we found that using our regularized spectrum as the initial guess resulted in substantial reduction to the required computational time. Details on both stages of the reconstruction algorithm can be found in Supplement 1.

### 3. RESULTS AND DISCUSSION

Tailoring the optical absorption of a given fishnet pixel can be achieved by appropriate choices of the array period and the widths of the interleaved silicon fins. The dispersion relation for each pixel can be found by modeling the fishnet region as two interleaved sets of orthogonal, strongly absorbing silicon high-contrast gratings (HCG). This differs from the usual applications of HCGs, e.g., very high reflectance mirrors for semiconductor lasers, for which the HCG material has very low absorption losses due to sub-bandgap operation [16,17]. It can be shown that the cutoff wavelength $\lambda_c$ for transverse-magnetic (TM) modes within a silicon high-contrast grating in air must satisfy

$$\frac{1}{n_{si}} \tan \left( \frac{\pi s}{\lambda_c} \right) - \tan \left( \frac{\pi (\Lambda - s)}{\lambda_c} \right) = 0,$$

where $n_{si}$ is the refractive index of silicon, $s$ is the width of the silicon waveguides, and $\Lambda$ is the period of the array. Transverse-electric (TE) mode cutoffs can be found by multiplying the first term in Eq. (1) by $n_{si}^2$. Mode cutoff wavelengths can therefore be tuned by varying both waveguide width and waveguide array period. Figure 2(a) shows a finite element method (FEM, COMSOL) calculation of the fractional absorption of normally incident light for an array of 2.7 μm tall silicon waveguides in air with a fixed period of 300 nm. The fractional absorption is only computed for the part of each waveguide (2 μm tall) that would correspond to the low-doped region of our device. Absorption of light in the heavily doped $p^+$ and $n^+$ layers is not expected to contribute significantly to the

![Fig. 2. (a) FEM calculated fractional absorption of TM-polarized light for a 300 nm period Si waveguide array (WGA) as a function of waveguide width overlaid with the analytically calculated TM mode cutoff wavelengths (red curves). (b) FEM absorption spectrum (blue line) for a WGA comprised of 75 nm wide Si fins and analytic TM2 mode cutoff wavelength (red-dashed line). (c) Normalized absorption density maps for light well below (i), at (ii) and well above (iii) the TM2 mode cutoff wavelength [indicated in 2(b)]. For clarity, the values in (i) and (iii) are multiplied by 2 and 20 respectively.](image)
measured photocurrent in each detector, as the photogenerated charge carriers would rapidly recombine in these regions. The widths of the vertical waveguides in the array are varied from 40 to 260 nm, and the wavelength of light is varied from 400 to 900 nm, encompassing most of the silicon detection window. The red curves show the cutoff wavelengths for TM modes $TM_2$, $TM_4$, and $TM_6$ as a function of waveguide width for a silicon WGA calculated using Eq. (1) with $\Lambda = 300$ nm. We note that mode $TM_6$ is the fundamental mode and has no cutoff, while odd TM or TE modes can only be excited with off-normal incidence illumination. [16, 18]. It can be seen that the fractional absorption in each waveguide peaks near unity when illuminated with a wavelength around that of the mode cutoff wavelength. It can also be seen that the cutoff wavelength and absorption peak wavelength both red-shift, in a near-linear fashion, with increasing waveguide width. We can exploit this fact to tailor the responsivity of our fishnet photodetectors, as the fishnet is merely comprised of two orthogonal sets of interleaved WGs. See Supplement 1 for further calculations of TE modes and the effect of array period. We also note that fishnet pixels, in contrast to WGs, should simultaneously support both TM and TE modes under normally incident linearly polarized illumination. It can also be seen that as the WGA modes become closely spaced, the absorption peaks associated with each mode begin to overlap. This is especially evident for higher-order modes. Figure 2(b) shows the FEM calculated absorption spectrum for a WGA comprised of 75 nm wide waveguides [indicated by the red circle in Fig. 2(a)]. The red dashed line indicates the first-order TM mode cutoff wavelength, $\lambda_c = 570$ nm, calculated using Eq. (1), which coincides with the peak wavelength of the simulated absorption spectrum. The spatial distribution of the normalized optical absorption at three wavelengths: (i) 430 nm, (ii) 570 nm, and (iii) 800 nm, are shown in Fig. 2(c). These wavelengths are, respectively, below, at, and above the cut-off wavelength for the 75 nm wide WGA. The calculated power absorption density is normalized to the total power of the exciting plane wave. One can find the total fractional absorption $A$ by integrating this quantity [with units in squared micrometers ($\mu$m)$^2$] over the device cross section. Note that the quantities plotted in Fig. 2(c)(i) & (iii) are multiplied by 2 and 20, respectively, so that the same color scale as case (ii) can be used. For case (i), we are below the cutoff wavelength of modes $TM_0$ and $TM_2$. The waveguides are thus dual-moded ($TM_0$ and $TM_2$ both propagate), and most of the absorption of these modes is associated with the shorter penetration depth and greater absorption of short-wavelength visible light in silicon [19] as would be the case for an unpatterned Si photodiode. For case (ii), we are near the cutoff wavelength of $TM_2$. The absorption thus mostly occurs within the top half of the waveguides. This is because near the $TM_2$ cutoff wavelength, the guided light has a large internal angle of incidence, increasing the effective path length traversed and boosting the total absorption. Whereas case (iii) is well above the cutoff, the waveguides are single-moded and freely propagate the incident light to the mesa below with little loss in the waveguide region. From these simulations we expect the photocurrent generated in the waveguide regions of the upper detector to exhibit responsivity peaks for shorter wavelengths and the mesa responsivities to peak in the red part of the visible spectrum, where the WGs are single-moded. Also of practical note is that the absorption density is larger at the silicon–air interfaces than in the core of the silicon waveguides. This is due to the boundary conditions imposed by arraying the slab waveguides, restricting the dispersion relation for the WGA, and in effect forcing the modes to propagate partly in air and partly in silicon [16]. The result of this is that a large proportion of the photogenerated carriers will be near the surface of the waveguides, making them susceptible to surface trap states, which are a natural consequence of the fabrication process and will reduce the detector’s external quantum efficiency [20].

Figure 3(a) shows the measured responsivity and external quantum efficiency (EQE) for both the fishnet and mesa detectors, with the fishnet WGA having width and period of 105 nm and 375 nm, respectively. The peak responsivity of the fishnet detector is 88 mA/W and occurs at a wavelength of 480 nm. For the mesa detector, the peak responsivity is 50 mA/W and occurs at a wavelength of 650 nm. It should also be noted that at a wavelength for which the fishnet responsivity is high, the mesa responsivity is low and vice-versa. This is because light that reaches the mesa detector must first pass through the fishnet region, which in this case acts as a passive filter, akin to conventional dye-based or thin film color filters. The maximum EQE for the fishnet detectors [shown in Fig. 3(a)] is 0.25, whereas the maximum measured mesa EQE from all fabricated detectors is 0.28 at 705 nm (not shown here). These values could be improved by passivating the sidewalls of the waveguide to reduce the interaction of charge carriers with surface trap states and recombination sites [21, 22]. Figure 3(b) shows the current-voltage curve for the same detector with and without illumination from the white LED lamp. A negative bias voltage corresponds to the fishnet region having reversed bias and acting as a photodetector and the mesa acting like a forward biased diode, and vice-versa for a positive bias. For this fishnet detector, the current measured at −1 V with illumination from the LED lamp was ∼100 times larger than the dark current. For this mesa detector, the current measured at +1 V with LED lamp illumination was ∼6 times larger than the dark current. Electrical characterization of all 23 pixels revealed that three (3) were defective, leaving 20 viable fishnet and mesa detectors for use in the microspectrometer chip. The inset of Fig. 3(b) is the response of the fishnet detector to light from the monochromator at a wavelength of 560 nm that has been optically chopped at 83 Hz. It can be seen that the response is a square wave. Some earlier generations of these devices showed very slow transient response both for the case of modulated illumination and for the case when the illumination was fixed, but the bias voltage switched. In addition, this temporal behavior was not stable. We attributed this behavior to electron beam damage of the native oxide layer during EBL [23] introducing charge trap states between the contact pad and the upper $p+$ layer. This issue was corrected by a brief RIE etch of the native oxide layer prior to forming the top contact pads.

The normalized responsivities of the twenty fishnet and twenty mesa detectors are shown as Figs. 3(c) and 3(d), respectively. As discussed, each detector contains a fishnet structure with unique geometric parameters, that is, waveguide width and array period ($\gamma$, $A$). For convenience, we thus use the term “fishnet number” to identify each detector [in Figs. 3(c) and 3(d)]. The geometric parameters of each fishnet, i.e., of each of the twenty pixels of our microspectrometer chip, are provided in Supplement 1. The peak responsivity wavelength for the fishnet detectors, that is, when the bias applied to each pixel is negative, shifts approximately linearly from 400 to 580 nm with increasing
fishnet number. When a positive bias is applied, the measured photocurrent originates from the mesa detectors. From Fig. 3(d), it can be seen that the responsivities of these detectors span the wavelength range 580 to 850 nm, with the center wavelengths shifting from 730 nm down to 660 nm with increasing fishnet number. The complementary nature of the responsivities of each fishnet and mesa detector pair allows us to collect spectral information from the visible to the near-infrared. It should also be noted that the linewidths (full widths at half-maxima, FWHMs) of the responsivity spectra of the fishnet and mesa photodiodes of each pixel are different. For example, for the pixel with fishnet number 9, the FWHMs are 160 nm and 280 nm for the fishnet and mesa photodiodes, respectively. This is an important issue to consider when implementing our reconstruction algorithm.

After measuring all 40 responsivity spectra of the photodetectors of our microspectrometer chip (20 fishnet and 20 mesa devices), the chip was illuminated with four different test spectra. The first was provided by a white light LED. The other three were generated by passing the output of the white light LED through colored glass filters. We chose to generate test spectra in this way because these spectra contain both narrow and broad spectral features. Such spectra are likely to be more representative of the spectra of what we expect might be a typical application of our device, namely, measuring the reflection spectra of materials (e.g., pigments and vegetation [24]) to identify them, as opposed to very narrow (e.g., from laser) or very broad (e.g., from black-body) test spectra. The photocurrents generated in each fishnet and mesa photodiode were then collected and input (with the responsivity spectra) to our two-stage reconstruction algorithm. For comparison we also measured the test spectra with a commercial spectrometer (Ocean Optics QEPro). The results are shown in Figs. 4(a)–4(d). It can be seen that the spectra reconstructed by our fishnet microspectrometer chip are in reasonable agreement with the spectra measured by the commercial spectrometer. The center wavelengths of the peaks in the test spectra are accurately determined. In addition, for the spectra with two peaks [Figs. 4(a) and 4(b)], the relative intensities of the peaks are reconstructed correctly. Furthermore, the FWHM linewidths of most spectral peaks reconstructed by fishnet microspectrometer are in agreement with those measured by the commercial spectrometer. However, it also apparent that the algorithm has less success for spectral regions at which intensities are smaller, producing spurious peaks in the reconstruction. To quantify the accuracy of a reconstructed spectrum, we compute the mean-square error (MSE) between it and the spectrum measured with the commercial spectrometer. The MSE values for the white, red, green, and blue reconstructions [i.e., Figs. 4(a)–4(d)] are 0.011, 0.067, 0.018, and 0.014, respectively. This indicates that the commercial and fishnet-based spectrometer are in good agreement across the visible spectrum. The narrowest-linewidth spectral feature successfully reconstructed has a FWHM of 16.5 nm at a center
wavelength of 432 nm and is shown in Fig. 4(d). The red test spectrum exhibited the largest error, due in part to the wider responsivity peaks and therefore lower spectral resolution associated with the mesa photodetector’s sensitive in this region. Figure 4(e) shows the computed CIE 1931 $xy$ color coordinates determined from the spectra measured by the commercial spectrometer and reconstructed by our fishnet microspectrometer chip. A D65 standard illuminant was used in the spectral conversion, with the white point located at (0.3127, 0.329). For the white LED lamp [Fig. 4(a)], the measured and reconstructed spectra give color coordinates of (0.33, 0.34) and (0.32, 0.31), respectively. Similarly, for the red, green, and blue spectra [Figs. 4(b)–4(d)], calculated color values are also in agreement. The red spectrum gives the largest discrepancy, which is consistent with the fact that its MSE is the largest. The mean Euclidean distance between the measured and reconstructed color value pairs is 0.056, which suggests that our microspectrometer is more suited to color identification applications such as machine sorting rather than those that require high color accuracy such as art restoration [25].

4. CONCLUSION

In summary, we have presented a novel nanostructured photodiode design with tailored responsivity spectra and used twenty such detectors to form an ultra-compact visible wavelength spectrometer chip. The peak responsivity wavelength of each detector is determined by the period and width of its fishnet pixel. These geometric parameters are set during the first lithography step for all detectors on the chip. Increasing the number of detectors in the chip can be readily achieved in our approach without additional steps, unlike the case for thin-film- and quantum-dot-based microspectrometers. The unique doping structure allows each pixel to operate in two complementary spectral regions by reversing the polarity of the bias voltage, in effect allowing two separate detectors to inhabit one on-chip footprint. We were able to use the known responsivities and measured photocurrents from each detector with machine learning computational techniques to reconstruct four visible test spectra. We found good agreement between the spectra from our chip and those from a commercial scientific spectrometer, with an MSE of 0.011 for a white LED spectrum. The results of the spectral reconstruction and CIE color value calculations demonstrate that our unique fishnet photodiode design is suitable for creating low-cost, moderate-fidelity spectroscopy and colorimetry systems on-chip, suitable for industrial and consumer applications.
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See Supplement 1 for supporting content.

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