Abstract—The responsivity spectrum of a photodetector is one of its key specifications. It ultimately originates from the combination of the absorption spectrum of the photosensitive region and the internal quantum efficiency. Many applications of photodetectors would benefit from an improved ability to tailor the responsivity spectrum. This is particularly true for color and multispectral imaging. The absorption spectrum of a bulk (unstructured) semiconductor is fixed however, being determined by its complex refractive index. Here, we review recent work that demonstrates that the absorption spectrum of a photodetector can be controlled via waveguide resonances in semiconductor nanowires. We discuss the physical interpretation for this phenomenon. We review work in which p-i-n photodiodes were incorporated into vertically-oriented silicon nanowires, and then used for color imaging. We review work in which tandem-style photodetectors were demonstrated, with a p-i-n silicon nanowire photodiode formed above an n-i-p planar silicon photodiode. We review work in which narrowband photodetection across the visible-to-infrared was demonstrated using germanium nanowires. Lastly, we describe related work in which silicon nanowires have been explored for other applications, namely solar cells.

Index Terms—Nanofabrication, nanolithography, nanomaterials, nanophotonics, nanoscale devices, nanowires, semiconductor nanostructures, photodetectors.

I. INTRODUCTION

There is currently considerable interest for a number of technology platforms for which photodetectors are critical elements. These include established platforms such as optical fiber communications and solar cells, as well as emerging technologies such as free space optical communications, laser radar (LIDAR) for self-driving cars, and advanced image sensors. The latter is a particularly important, as image sensors are currently being manufactured in very large volumes, being ubiquitous components of smartphones. The responsivity spectrum of a photodetector is one of its key specifications. It stems from a combination of its absorption spectrum and internal quantum efficiency. For a bulk unstructured semiconductor (e.g. wafer), the absorption spectrum is fixed, as it is determined by the complex refractive index. In this paper, we review recent work demonstrating photodetectors for which waveguide resonances in vertically-oriented semiconductor nanowires are used to control the absorption spectra. We furthermore describe how these and related effects are being applied in another field, namely photovoltaics.

Numerous applications of semiconductor nanowires have been pursued in recent years. Electronics has been of particular interest [1-11], including both field effect transistors for beyond-CMOS as well as more fundamental studies. Nanowires have been studied for battery applications [12-14], solar cells [15-17], nanogenerators [18,19], and chemical/biological sensors [20-27]. Applications in optoelectronics have included photodetectors for image sensors [28] and lasers [29-31]. Interestingly, prior to the work reviewed in this paper, few experimental studies had been performed that made use of the fact that vertically-oriented nanowires support optical waveguide modes for photodetection. In References [32 -36], it was shown that leaky mode resonances could be used to spectrally engineer light absorption. The nanowires were horizontally oriented however. In this paper, we discuss the opportunities presented when the nanowires are vertically-oriented.

For vertically-oriented nanowires to be used in photodetectors in a practical fashion, it is critical that there exist high yield and economic nanofabrication methods to manufacture them. The vapor-liquid-solid method [37] is the main method by which silicon nanowires are formed. It
involves growing nanowires from catalyst (e.g. Au) particles on Si substrates in a furnace. In general, however, it produces nanowires with a variety of diameters, lengths, orientations and positions, unless special steps are taken [38]. Such nanowires (with a variety of sizes, etc.) can be readily used for many scientific investigations, but are unsuitable for our application, in which vertically oriented Si nanowires of a predetermined diameter are needed. It has been shown that lithography and inductively coupled reactive ion etching (ICP-RIE) offer a means to achieve this goal. As illustrated schematically as Fig. 1a, the positions, shapes and sizes of the resultant nanowires are determined by the lithographically-defined etch mask and the duration and rate of the ICP-RIE process. Several works have employed this method for forming vertically-oriented silicon nanowires for photonic applications. Some examples are as follows. Seo et al fabricate square arrays (period 1 µm) of Si nanowires with heights of 1 µm, and radii of 45 nm to 70 nm, demonstrating that waveguide resonances control over absorption ([39], discussed in next section). Walavalkar et al produce very small diameter (< 10 nm) pillars by following the etching step with oxidation, and measured visible and near-infrared photoluminescence [40]. Khorasaninejad et al [41] and Walia et al [42] produce arrays of Si nanowires for colorimetric refractive index sensing. Khorasaninejad et al also study the bunching characteristics of such arrays [43]. For these and other optics-type applications of vertically-oriented silicon nanowires, control over the dimensions (e.g. diameter and height) and shape (e.g. tapered vs untapered) is critical. These and other works have shown that this method (lithography/etching, Fig. 1a) achieves this. In Fig 1b, for example, four arrays of etched Si nanowires are shown, with diameters ranging from 80 to 140 nm [44]. These are photodetector devices and are discussed further later.

II. SELECTIVE LIGHT ABSORPTION IN SEMICONDUCTOR NANOWIRES: PHYSICAL MECHANISM

Seo et al obtain images of their arrays of etched nanowires using a conventional bright-field optical microscope (Fig 2, [39]). Each array has an overall extent of 100 µm × 100 µm, and contains 10^6 nanowires (period: 1 µm). The nanowires have heights of 1 µm. It can be seen that the arrays display a striking variety of colors, ranging from red to purple, blue and green, as the radius is increased. Seo et al further demonstrate the possibilities for structural color applications by patterning the letters “S”, “E”, “A”, and “S” from Si nanowires of different radii (Fig 2b, [39]). In the zoom-in of the letter “A” (Fig 2b, right side), individual Si nanowires can be readily seen, appearing as blue dots.

![Fig. 1. a). Reactive ion etching step of nanowire fabrication process. b). SEM images of square arrays (period 1 µm) of nanowires (height: 2.7 µm). Each array is 100 µm × 100 µm and contains nanowires with radii of 80 nm, 100 nm, 140 nm, and 120 nm (clockwise from top left). Reprinted (adapted) with permission from Ref [44]. Copyright 2014, American Chemical Society](image1)

![Fig. 2. a). Brightfield optical microscope images of square arrays (period 1 µm) of Si nanowires with radii (R) ranging from 45 to 70 nm, and heights of 1 µm. b). Brightfield optical microscope image of Si nanowire pattern. The letters “S”, “E”, “A”, and “S” comprise collections of nanowires with radii of 70 nm, 60 nm, 50 nm, and 40 nm, respectively. Nanowires in lines above and below letters range in radius from 75 nm to 35 nm (left to right). Reprinted (adapted) with permission from Ref [39]. Copyright 2011, American Chemical Society](image2)
other effects associated with periodicity. This is not the case however. Indeed, as noted in Refs [39] and [46], the multicolored appearance of the nanowires can be understood by considering them as waveguides. This is discussed below.

Numerical methods such as the finite difference time method [47] or the finite element method [48] allow one to readily simulate the absorption spectra of nanowire arrays such as those of Fig. 1 and 2. While rigorous, these approaches often only provide partial physical insight. Seo et al [39, 46] find that physical insight can be gained by considering each nanowire as acting as a waveguide (Fig. 4a).

Seo et al note [39, 46] that the multicolored nature of the nanowires (Fig. 3 and Fig. 4) can be understood by considering the wavelength-dependence of the field profile of the fundamental guide mode (HE₁₁ mode). To this end, Seo et al plot the field distribution of the fundamental guided mode of a silicon nanowire of radius 45 nm at three representative wavelengths [39]. The results are shown as Fig. 4b-d, and are of the y-component of the electric field. The nanowire axis is in the z-direction, and the results are plotted in the transverse plane (xy plane). It can be seen that, at short wavelengths (\(\lambda = 400\) nm, Fig. 4b), the mode is highly confined to the nanowire core. One should therefore expect that if the incident light (Fig. 4a) is a normally-incident plane wave, then its coupling to the mode at this wavelength will not be strong. This is because the overlap between the incident plane wave and the highly confined waveguide mode is not high. At this wavelength, therefore, little of the incident light will be coupled to the fundamental mode of the nanowire. The incident light will be reflected at the planar air-silicon surface (Fig. 4a). This is consistent with short-wavelength behavior seen in the experimental results (Fig. 3). Seo et al consider an intermediate wavelength (\(\lambda = 547\) nm, Fig. 4c). It can be seen that the extension of the fields beyond the nanowire core (i.e. into air) is much greater at this wavelength than for \(\lambda = 400\) nm. The incident plane wave will therefore couple much more strongly to the mode than for \(\lambda = 400\) nm. It can also be seen from Fig. 4c that the fields within the nanowire are appreciable. As the permittivity of silicon has an imaginary component at this wavelength, power dissipation will be associated with these fields. At this intermediate wavelength (\(\lambda = 547\) nm), therefore, an appreciable portion of the incident light will be coupled to the waveguide mode and absorbed, thereby resulting in decreased reflection. This is consistent with the reflectance dip observed around this wavelength in the experimental spectra (Fig. 3). Seo et al next consider a long wavelength (\(\lambda = 650\) nm, Fig. 4d). It can be seen that the fields are highly extended from the nanowire core. One should thus expect that coupling from the incident plane wave to the fundamental mode of the nanowire will be strong. It can also be seen that the fields inside the nanowire are not strong. One should thus expect that much of the incident light will be coupled to the nanowire’s fundamental mode, but that little absorption will occur, and the mode will be reflected at the air-silicon interface. At long wavelengths (here \(\lambda = 650\) nm), one should expect appreciable reflection from nanowire arrays. This is consistent with the experimental results (Fig. 3). The waveguide mode physical interpretation furthermore would predict that increasing the nanowire radius would result in the same behavior at longer wavelengths (provided that the permittivity does not vary too drastically with wavelength). This is indeed seen in experiments (Fig. 3).

**III. COLOR IMAGING WITH SILICON NANOWIRE PIXELS**

Image sensors for color imaging usually employ absorptive dye-based filter arrays, with one filter per photodetector. In recent years, there has been interest for the development of alternative approaches, due to challenges faced by the
traditional dye-based filters, such as photostability. An alternative approach that has been put forward is that of plasmonic color filters [49-51]. These have the advantage that only one material is needed and that transmission spectra can be tailored in a flexible manner. Plasmonic filters would generally be used in the same manner as traditional dye filters, i.e., formed over the detectors to transmit certain wavelengths, while absorbing (or reflecting) others. The light that is absorbed in plasmonic or dye-based filters is of course not converted to photocurrent in the underlying detector. As discussed in the previous sections of this paper, vertically-oriented Si nanowires have absorption spectra that can be tailored by appropriate choice of nanowire radius. Park et al show that spectral filters can be realized by embedding vertically-oriented Si nanowire arrays in transparent polymers [45]. Park et al also demonstrated color and multispectral imaging using such filter arrays [52]. In that work [52], the nanowire filters were used in a conceptually-similar way to plasmonic or dye-based filters, i.e., the filter arrays were placed above detector arrays, with the transmitted light converted to photocurrent and the absorbed light “discarded”. Silicon nanowire filters present an additional opportunity, however. Like plasmonic and dye based filters, silicon nanowires can filter transmitted light. However, unlike plasmonic and dye based filters, in silicon nanowires, the absorbed light can be converted to signal (i.e. photocurrent). As we describe in this section, Park et al demonstrate this by forming p-i-n photodiodes in the nanowires (Fig. 5a, [44]). When combined with top and bottom electrical contacts, the electron-hole pairs generated by absorbed photons can be collected.

The vertically-oriented Si nanowires of Ref [44] are produced by e-beam lithography and reactive ion etching (Fig. 1a), i.e. the same method as that used for Refs [39, 45, 52]. One difference to Refs [39, 45, 52] however is that the starting wafer contains intrinsic (lightly doped n−) and p+ doped layers on an n+ substrate, rather than being of uniform doping. In addition, as this is a photodetector device, electrical contact to the tops of the nanowires needs to be made. This is achieved using the transparent conductor indium tin oxide (ITO). To support the ITO layer mechanically, the polymer poly-methyl-methacrylate (PMMA) is used. The appropriate thickness is obtained by first spinning on the PMMA onto the wafer to a thickness that exceeds the heights on the nanowires. The PMMA is then etched in an oxygen plasma until the tops of the nanowires protrude. Four photodetectors are realized in the work of Ref [44], each comprising a square array (period 1 μm) of nanowires with an overall extent of 100 μm × 100 μm, i.e. with 10^4 nanowires per photodetector. The four photodetectors differ with respect to the radii of the constituent nanowires (R= 80 nm, 100 nm, 120 nm, and 140 nm). SEMs of the nanowires after etching are shown as Fig. 1b. Adding the PMMA and ITO results in the top electrodes of the four photodetectors being connected electrically. In order to isolate the detectors, a wafer scribe tool is used to cut the ITO layer, with the results shown as Fig. 5c. The nanowire photodetector chip is then attached to a circuit board. Gold wires attached with silver paste provide the necessary electrical connections from the nanowire photodetector chip to the circuit board. This allows the realization of a camera for color imaging (Fig. 5c). To convert the data measured from the nanowire pixels to color images, the responsivity spectra of the nanowire photodetectors must be known. We next discuss these spectra (Fig. 6).

Fig. 6. Measured responsivity spectra of arrays of nanowires with different radii (R), with associated waveguide modes as indicated. Reprinted (adapted) with permission from Ref [44]. Copyright 2014, American Chemical Society

Fig. 5. a). Schematic illustration of Si nanowire photodetector. From [44]. b). Optical microscope image of four nanowire array photodetectors. Scalebar: 100 μm. Reprinted (adapted) with permission from [44]. Copyright 2014, American Chemical Society. c). Photograph of homebuilt camera that employs nanowire photodetectors for color imaging. From [53].
Park et al measure the responsivity spectrum of each nanowire photodetector by illuminating it with light from a halogen lamp that has been spectrally filtered by a monochromator [44]. The nanowire photodetector is operated at zero bias voltage. The photocurrent from the nanowire photodetector is measured by a picoammeter. The power of the light incident upon the device is measured using a reference silicon photodetector. This allows the responsivity spectrum of each device to be found (Fig. 6). It can be seen that the responsivity spectra display a number of peaks. These can be associated with various waveguides modes (HE$_{11}$, HE$_{12}$, and HE$_{13}$). As expected, each of these shifts to longer wavelengths as the nanowire radius is increased.

Park et al perform imaging experiments [44] using the homebuilt camera shown as Fig. 5c. A camera lens (Pentax focal length 50 mm) operated at an f-number of 2.0 forms an image. The circuit board is placed at the location of the image. The board is mechanically scanned over 180 × 128 positions, with the overall extent of the scanned area being 25.57 mm × 18.15 mm. At each scan position, the photocurrents from the four photodetectors are recorded. Park et al then convert these photocurrent maps to color images (Fig 6). The conversion method is discussed below.

IV. TANDEM PHOTODETECTORS INCORPORATING VERTICALLY-ORIENTED SILICON NANOWIRES

As discussed in the previous section, in conventional color image sensors, color filter arrays (e.g. dye-based) are formed over photodetector arrays. Each color filter transmits a certain spectral band (e.g. red, green or blue) to its corresponding (underlying) photodetector. Park et al demonstrate that Si nanowire arrays embedded in transparent films can function as filter arrays and, when placed over a photodetector array, enable color and multispectral imaging [52]. The previous section reviewed work in which it is demonstrated that incorporating p-i-n diodes into Si nanowires allows absorbed light to be converted to photocurrent [44]. In this section, we discuss the experimental demonstration of a tandem photodetector that consists of a nanowire array photodetector (p-i-n photodiode) formed over a planar photodetector (n-i-p photodiode) [56]. In other words, the Si nanowire array is formed over a planar photodetector, a configuration that is analogous to how a conventional color filter (e.g. dye-based) is formed over a planar photodetector in a color image sensor. The key difference however is that the Si nanowire array converts absorbed light to photocurrent. We discuss the device, its fabrication, and its experimental characterization.

The device is shown schematically as Fig. 7a. It consists of a nanowire array p-i-n photodiode that is formed over a planar n-i-p photodiode. The starting point in the fabrication is a p-type doped Si wafer, on which a number of films are grown epitaxially. From the top of the wafer, the layers are as follows: p+/n-/n+/n-, with thicknesses of 0.2 μm/2 μm/1 μm/4 μm, respectively. Park et al produce the nanowires by e-beam lithography, metal mask evaporation, lift-off, and reactive ion etching. To define the planar photodetector, it is etched into a mesa. In a manner similar to that employed for the photodetector in the previous section, ITO is used for the realization of a transparent top electrode, with PMMA again used for mechanical support. Park et al use gold wire and silver epoxy to establish electrical contacts to the three contacts of the device (ITO, n+, substrate, Fig. 7a). A color optical microscope image of the device after this is done is shown as Fig. 7b. Park et al demonstrate two devices. In the first, the constituent nanowires have radii of 100 nm. This leads to them having an orange appearance (Fig. 7c). In the second, the nanowires have radii of 120 nm, resulting in them appearing green (Fig. 7d). Park et al characterize these devices in a manner similar to that employed for the devices in the previous section. Light from a halogen lamp is filtered by a monochromator and then focused onto the device with a homebuilt microscope. Photocurrent is measured from the top
(i.e. nanowire detector) and bottom (i.e. planar detector) devices using a picoammeter. The optical power incident on the device is measured with a reference photodetector. This allows the responsivities for the nanowire devices (Fig. 7e) and planar devices (Fig. 7f) to be found. It can be seen that the nanowire devices exhibit peaks in their responsivity spectra. These are associated with waveguide modes supported by the nanowires, and shift to longer wavelengths for the larger radius nanowire device as expected. It can also be seen that the planar detectors have reasonable responsivities (~0.27 at \( \lambda = 630 \text{ nm} \)), being similar to conventional silicon photodetectors [57]. The responsivity spectra exhibit ripples. These originate from the PMMA film with embedded nanowires acting as a Fabry-Perot cavity, thereby modulating the spectrum of the light transmitted into the underlying planar photodetector. Some differences can be seen between the responsivities of the two devices in the spectral range from below 500 nm to around 600 nm, with device #2 having a lower responsivity than device #1. This originates from the fact that Si nanowire array #2 has an absorption peak in this range, thus reducing the transmission to the underlying photodetector. Thus Si nanowires are thus acting as optical filter as intended. The filtering effect is not especially pronounced, however. This might be a promising topic for future studies of devices with this configuration.

**Fig. 7. a).** Schematic illustration of tandem photodetector, comprising Si nanowire photodiodes (p-i-n) formed above planar photodetector (n-i-p). b)-d). Optical microscope images of tandem photodetectors. b). Low magnification image, including gold wires that contact to top (ITO) and intermediate (mesa) layers. Higher magnification images of tandem photodetectors containing nanowires with radii of c). 100 nm and d). 120 nm. Insets show magnified views of nanowire arrays. e). Measured responsivities of nanowire photodetectors. f). Measured responsivities of corresponding planar photodetectors. Reprinted (adapted) with permission from Ref [56]. Copyright 2017, American Chemical Society

V. **NARROW-BAND INFRARED PHOTODETECTORS BASED ON GERMANIUM NANOWIRES**

As discussed in previous sections, color and multispectral imaging has been demonstrated with photodetectors based on Si NWs [44, 52]. These devices have functioned over the visible to near-infrared spectral range, due to the fact that Si has a bandgap of \( \sim 1.11 \text{ eV} \) [58]. There are many important applications [59] of imaging in the short-wave infrared (SWIR) spectral region, however, including in the semiconductor industry [60] and in biology and medicine [61]. This motivates Solanki et al [62] to demonstrate visible-to-SWIR photodetectors using Ge NWs. It is the smaller bandgap (0.67 eV, [58]) of Ge that allows extension into the SWIR region. In this section, we review this work.

The device that Solanki et al demonstrate is shown schematically as Fig. 8a. Like the Si NW devices described in previous sections, the Ge NWs are formed by reactive ion etching. The starting material is a p+ doped Ge substrate, on which intrinsic and n+ doped Ge layers are grown. The device of Solanki et al is different in an important way however. In the previous Si NW work of Refs [44, 56], the NWs are embedded in PMMA, to provide mechanical support to the ITO layer that forms the transparent top contact. That the NWs are surrounded by PMMA rather than air means that the refractive index contrast between the NW and the surrounding medium is lowered. Solanki et al mitigate this via a “wrap-around” electrical contact (Fig. 8a), described further below.

**Fig. 8. a).** Schematic illustration of narrowband visible-to-infrared photodetector based on germanium nanowires (Ge NWs). b). Scanning electron micrographs (SEMs) of etched Ge nanowires with diameters of b-i). 75 nm, b-ii). 125 nm, b-iii). 175 nm. Reprinted (adapted) with permission from Ref [62]. Copyright 2017, American Chemical Society

Solanki et al use reactive ion etching with an Al disk hard mask defined by e-beam lithography to produce their arrays of Ge NWs. The NWs have heights of 2 \( \mu \text{m} \). As discussed, the
starting point is a highly doped Ge wafer (p+) on which intrinsic (1.5 \( \mu m \)) and n+ doped (300 nm) layers are grown epitaxially. Scanning electron micrographs (SEMs) of the NWs after etching with various diameters are shown as Fig. 8b. The “wrap-around” electrode is formed as follows. The Al from the tops of the NWs are removed by immersing the sample in Microposit MF CD-26 developer. Atomic layer deposition of Al\(_2\)O\(_3\) to a thickness of 6 nm is then performed. PMMA is then spun onto the sample. Four spin coating steps are used, thereby ensuring that the NW arrays become completely encased in PMMA. The PMMA is then etched in an oxygen plasma until the tips of the NWs are exposed. The sample is then immersed in hydrofluoric acid (diluted to 1%) to etch the Al\(_2\)O\(_3\) from the exposed NW tips. The PMMA is then removed by soaking the sample in acetone. A fresh layer of PMMA (200 nm thick) is then spun on to the sample. The purpose of this layer is to embed the doped (p+) base of the nanowires for electrical isolation. An oxygen plasma etch is carried out to ensure that any PMMA on the NW sidewalls is removed. ITO is then sputtered onto the sample, making electrical contact to the tops of the NWs, but electrically isolated from the middle intrinsic section and the (p+ doped) base of the NW. To increase the conductivity of the ITO, gold (Au) is evaporated onto the sample to a thickness of 30 nm. The NW photodetectors are then ready for testing. The NW photodetectors have diameters of {75 nm, 100 nm, 125 nm, 150 nm, 175 nm, 200 nm, 225 nm, 250 nm}. The fabrication method described above results in these devices being collected electrically in parallel, as they share top (ITO) and bottom (p+ substrate) electrodes. Their photoresponse can be nonetheless characterized separately, as they can be illuminated individually. We next discuss the results of this characterization.

Solanki et al simulate the optical properties of their NW devices using the FDTD method (Fig. 9a). These are for idealized structures, i.e. Ge NWs on Ge substrates (without the Al\(_2\)O\(_3\) and other layers). Solanki et al perform scanning electron microscopy that reveals that the NWs are tapered, with different top and bottom diameters. The tapered nature of the NWs is taken into account in the simulations of Fig. 9a. For brevity, the diameters referred to in Fig. 9 are the values employed in the e-beam lithography step. The measured top and bottom diameters of the NWs are given in [62]. The simulations of Fig. 9a are of absorption efficiency, i.e. the fraction of light absorbed by the section of the NW that would be the intrinsic region of the device. This section is taken as starting at 300 nm from the tops of the NWs, and extending by a distance of 1500 nm. A few observations can be made from the results of Fig. 9a. It can be seen that the absorption efficiency is high, being near unity for several NW devices. As expected, the absorption efficiency spectra exhibit peaks that move to longer wavelengths as the NW diameter increases. At shorter wavelengths, the spectra display ripples that Solanki et al attribute to Fabry-Perot resonances [63, 64]. Some sharp features occur near \( \lambda = 1000 \text{nm} \). Solanki et al attribute these to grating modes that are coupled to when the free space wavelength matches the grating period.

![Fig. 9. Simulations and experiments for Ge NW photodetectors. a). Simulated absorption efficiency spectra for arrays of Ge NWs with different diameters on Ge substrate. b). Experimentally-measured external quantum efficiency (EQE) spectra for Ge NW devices with different diameters. c). Simulated absorption efficiency spectra for Ge NW structures with geometries chosen to match those of fabricated devices. d). Simulated EQE spectra, obtained by combined electrical-optical modeling of Ge NWs, with assumed surface state density \( S = 1 \times 10^{13} \text{cm}^{-2} \). Reprinted (adapted) with permission from Ref [62]. Copyright 2017, American Chemical Society](image_url)

Solanki et al next measure the external quantum efficiency (EQE) of their devices. This is done by illuminating them with
light from a lamp that is filtered by a monochromator and focused by a homebuilt microscope onto the device. The focused spot of light has a diameter of \( \sim 80 \mu m \), i.e. smaller than the overall extent of each NW array device (100 \( \mu m \times 100 \mu m \)). In this way, Solanki et al test each device individually. The optical power incident on each device is determined with reference Si and InGaAs photodetectors. Solanki et al find the measured responsivities of their devices by dividing the measured photocurrents by the incident optical power. These responsivities are then converted to EQE and presented as Fig. 9b. The measured results are similar to the simulations of Fig. 9a in that they show peaks that move to longer wavelengths for larger diameter NWs. Like the simulations of Fig. 9a, the experimental EQE spectra also show peaks at around \( \lambda = 1000 \text{ nm} \) (though not for all devices). While the experiments and simulations are similar, there are some noticeable differences. The EQE spectra that Solanki et al measure exhibit sharp narrowband peaks with full-widths-at-half-maximum (FWHMs) spanning 40 to 155 nm. On the other hand, the simulated absorption efficiency spectra have peaks with FWHMs from 115 to 250 nm. In addition, the fabricated devices have a peak EQE to \(-0.076\) (\( d = 200 \text{ nm} \) NW device), while the simulated absorption efficiencies are nearly unity. To understand these differences, Solanki et al carry out further investigations. These are described next.

Solanki et al consider that the differences between simulations (Fig. 9a) and measurements (Fig. 9b) might be due to the simulated structure not matching the fabricated device. Solanki et al therefore re-do the simulations, but with the other layers and other materials of the device taken into account. In other words, the Al\(_2\)O\(_3\), ITO, Au and PMMA layers are included. The results are shown as Fig. 9c. It can be seen however that the key differences, i.e. the value of the EQE and the FWHMs of the peaks, between simulations and experiments remain. This leads Solanki et al to consider another possible reason for the discrepancy. In making the comparison to the simulated optical absorption efficiency (Fig. 9c) to the measured EQE (Figure 9b), the implicit assumption being made is that the internal quantum efficiency (IQE) is unity, i.e. that each absorbed photon is converted to an electron-hole pair that is then collected with unity efficiency. Solanki et al note that in NWs, charge transport is influenced by doping and presence of surface and interface states [65-67]. The latter come about in part from the fact that the semiconductor lattice is terminated at the NW surface, thereby modifying the electronic potential and leading to new electronic states that can trap charge carriers [68-70]. Solanki et al therefore modify their approach to include electrical modelling. This is performed with a commercial finite element package (COMSOL Multiphysics). Solanki et al perform carrier transport simulations, with the goal of determining the collection probability as a function of position over a cross section through the NW. Solanki et al then combine this with an optical generation rate map that is obtained by the optical (FDTD) simulations to produce a collection rate map over the NW. The final EQE spectrum for the nanowire being considered is then obtained by integrating this quantum efficiency map over the NW. The results are shown as Fig. 9d. It can be seen that the simulations that incorporate both electrical and optical modelling agree much better with the experimental results than the optical-only simulations. The model take the surface state density to be \( 1 \times 10^{13} \text{ cm}^{-2} \). Solanki et al note that the experiments demonstrate that the EQE spectra are strongly influenced by an interplay between optical and electrical properties, and while this leads to narrowband photodetection, in other applications it might be better to reduce surface state density. This might be promising topic for future study.

VI. BEYOND IMAGING: APPLYING THE NANO-OPTICS OF VERTICALLY-ORIENTED NANOWIRES TO PHOTOVOLTAICS

In this paper, we have reviewed several works in which the nano-optical properties of vertically-oriented nanowires have been used for applications in color and multispectral imaging. There are of course many other applications of the nano-optics of nanowires. One example is the optical metasurface [71-75] (a concept related to the high contrast grating [76-78]) although the nanostructures frequently do not have circular cross sections and are often thought of as nanofins rather than nanowires. A complete review of all such applications is beyond the scope of this paper, and we instead select one application, namely photovoltaics. Exploration into the use of nanowires in solar cells is motivated by their potential to lower the cost-per-watt of such devices. One way to reduce cost involves using thinner semiconductor films [79, 80], but in general this approach reduces efficiency as less light is absorbed in the solar cell. Arrays of vertically-oriented NWs present a means for mitigating this, as they can increase the coupling of light into the solar cell and increase the absorption through light trapping [81]. A number of theoretical and experimental works have thus been carried out on NW photovoltaics and related topics [82-101].

One of the challenges faced by NW-based photovoltaics is concerned with their design. Typically, this has been approached by performing brute force numerical electromagnetics simulations of the light absorbed in the NWs as a function of their geometric parameters (period, radius, height, etc.). This is then followed by electrical modeling to predict performance. This approach has the following disadvantages. It is generally time consuming, as there are a number of parameters that must be varied. It furthermore does not provide the designer with much insight into which configuration is optimal. Here, we briefly review the work of Sturmberg et al [81], who address this question by developing a semi-analytic approach to evaluate the optimal NW array parameters to maximize charge generation. They present results for a square array (period \( d \)) of NWs with radii \( a \) and height \( h = 2.33 \mu m \) (Fig. 10a). The filling fraction is thus given by \( f = \pi \times a^2/d^2 \). Here we discuss results in which the NWs are indium phosphide (InP) and the substrate is SiO\(_2\), but Sturmberg et al also present results for other materials (Si, Ge, GaAs) and for other NW heights. By comparison with electromagnetics simulations (i.e. brute force), Sturmberg et al show that their analytical method correctly identifies the optimal region of parameter space.
The ability of the NWs to support guided resonance modes is of course critical to the properties of NW arrays here considered for photovoltaics. So far in this paper we have have considered arrays in which the NWs are relatively sparse. Our physical interpretation has thus been based on thinking about the NWs as supporting optical fiber-type modes. Sturmberg et al, however, note that when the NWs are closely-spaced, this picture is not correct. Instead, one should consider the effect of the lattice and consider the Bloch modes of the system. They refer to these as the “key modes” \cite{81, 91}. Sturmberg et al note that one might expect that an optimal design to include NWs with large radii, as these will support a larger number of key modes and thus exhibit stronger absorption. They note however that the absorption of the material and the solar spectrum should be taken into account. They thus argue that one should consider the number of key modes that are within the wavelength range $\lambda_1 < \lambda < \lambda_g$, where $\lambda_1 = 310 \text{ nm}$ represents the lower limit of the solar spectrum and $\lambda_g$ is the bandgap wavelength of the NW material ($= 922.5 \text{ nm}$ for InP). Sturmberg et al thus employ waveguide theory (transcendental equation for HE modes) to vary possible NW radii and determine when the key modes enter and leave the spectral range $\lambda_1$ to $\lambda_g$. These radii are indicated on Fig. 11a, with black curves denoting when an additional mode enters the spectral range and greens curves when a mode leaves. The number of key modes present in the regions between the curves is also indicated in Fig. 11a. The fundamental HE$_{11}$ mode is not included in Fig. 11a. Sturmberg et al note that it does not contribute a large absorption peak, and is thus relatively unimportant in this optimization method. Sturmberg et al next vary the array period, while keeping the filling fraction fixed. They find that as the array period increases, long wavelength absorption increases initially, then decreases. They attribute the decrease to a rise in transmission, due to the larger number of diffraction channels in the substrate that can propagate energy away from the NW array. They therefore argue that the NW array period should be made small enough so that only one channel (zero order diffraction mode) exists in the substrate. This can be achieved by setting the array period to be smaller than $\lambda_1/n_{sub} = 213 \text{ nm}$, but Sturmberg note this can be relaxed a little as short wavelength photons tend to be strongly absorbed. Instead, they choose the criterion that the array period should be smaller than $\lambda_{avg}/n_{sub} = 456 \text{ nm}$, where $\lambda_{avg}$ is the average wavelength of solar spectrum photons over the spectral range $\lambda_1$ to $\lambda_g$. This array period is shown on Fig. 11b by a dotted vertical line, with the (undesirable) high transmission region that occurs at larger array periods indicated with blue and magenta shading. Sturmberg et al next vary volume fraction $f$, while keeping array period fixed. They find that absorption decreases across the spectrum at higher volume fractions due to an increase in reflectance. They interpret this as being due to an increase in the effective refractive index. Sturmberg et al thus choose the criterion that volume fraction kept small enough so that the reflectance of an effective medium \cite{102-104} that represents the NW array is smaller than the transmittance of the effective medium. This volume fraction is indicated on Fig. 11b by a dash-dot horizontal line, with the (undesirable) high reflectance region indicated by red and magenta shading. The white region of Fig. 11b thus represents the parameter space for which transmission and reflection from the array are not excessive. Similarly, the white regions of Fig. 11a are those having two or more key modes. Sturmberg et al argue that the union of these white regions (of Fig 11a and 11b) thus represents optimal NW array designs.

To test their method, Sturmberg et al simulate the short circuit current density of the InP NW array as a function of period and volume fraction. The optimal region found by the semi-analytical method of Sturmberg et al, i.e. the union of the white regions of Fig. 11a and 11b, is indicated by thick curves on Fig. 12. It can be seen that the optimal choice (blue dot of Fig. 12) as found by the brute force numerical simulations is indeed contained within the optimal region predicted by the model. This confirms the efficacy of the technique.
VII. CONCLUSIONS

One of the most intensively investigated structures in the field of nanotechnology has been the semiconductor nanowire. A number of factors have contributed to this interest. Nanowires present the opportunities for heterojunctions to be formed without the lattice mismatch issues faced in traditional planar (bulk) configurations. The inherently high surface-area-to-volume ratios of nanowires permit important opportunities for high performance transistors and for chemical/biological sensors. Nanowires also have unique mechanical properties that can be useful for various applications. In this work, we argue that the fact that vertically-oriented nanowires support optical waveguide-type modes presents a further compelling reason for the study of semiconductor nanowires that complements those discussed above. We review work in which this phenomenon has been applied to photodetectors. We discuss a physical interpretation of light matter interactions in nanowires. We discuss work in which these interactions are employed in silicon nanowire photodetectors for color imaging without the need for additional filters. We discuss work in which silicon nanowire photodiodes are incorporated into a tandem device that includes a planar silicon photodiode. We discuss work in which these effects are extended to the short-wave infrared via germanium nanowires. While progress has been made in photodetectors based on vertically-oriented nanowires, many questions remain. Possible future studies could include the use of surface passivation to improve responsivity and the extension of this technique to other spectral ranges. We also see the development of design techniques that provide physical intuition as being highly useful, and review one such technique for photovoltaics. We anticipate that that the topic of vertical nanowires for photodetection will offer many more fruitful opportunities for further study in the future. We expect that there are other configurations and applications that could offer improved performance and/or new functionalities.

REFERENCES


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