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Fully Integrated CMOS-Compatible Photodetector with Intrinsic Gain and Red-Green-Blue Color Selectivity

by

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ABSTRACT

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Currently, image sensors are hybrid devices, combining semiconductor photodiodes with off-chip color filters of different materials to convert wavelength-selected light into useful photocurrent. Here we demonstrate a fully integrated, metal-semiconductor-metal (MSM) photodetector and plasmonic color filter fabricated entirely from Aluminum and silicon designed to detect light in selected wavelength bands across the visible spectrum. The device produces photocurrent gain by carrier accumulation, while exploiting the evanescent field of the surface plasmon for both wavelength selectivity and photocurrent enhancement. With a maximum responsivity of 12.54 A/W and a full-width-half-maximum (FWHM) spectral selectivity of ~100nm, this high performance photodetector has potential for immediate applications in color-selective low-light imaging and high pixel density imaging sensors.
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accumulation of photo-generated carriers provides photocurrent gain. The grey region denotes the linear operating regime, allowing for a direct measure of the device conductance. (b) Current-voltage curves for a device operated in the linear regime illuminated by different laser powers. Increasing the laser power increases the device conductance. (c) The change in conductance as a function of laser power. The calculated device efficiency is 5.8%, or an equivalent responsivity of 26.2 mA/W.
Chapter 1

Introduction

Over one billion silicon-based image sensors were produced worldwide in the last year alone. Typically, imaging sensors use p-n or p-i-n junctions to separate and collect photo-excited electron-hole pairs. Despite the high quantum efficiency of the absorption process, a single incident photon can only provide one electron’s worth of current. For low-light situations and high-density pixels, a single photodiode produces small amounts of photocurrent, requiring extremely low-noise electronics to amplify the signal. In addition, silicon-based image sensors absorb over a broad spectral range, requiring color filters for spectral selectivity. In contemporary image sensors, the color selection is performed with dielectric or organic dye filters, which impose practical limitations on scalability and durability. With small pixel sizes, the integration of dielectric filters with image sensors becomes challenging due to the need for complex and time-consuming alignment procedures. The use of on-chip organic dyes is limited by their durability, as
currently available dyes degrade over time under exposure to ultraviolet light.\textsuperscript{2} Instead, a durable photodetector with built-in gain and color selectivity would be preferable for future imaging applications. This thesis will focus on a CMOS-compatible imaging sensor that takes advantage of both plasmonic and charge-trapping effects for a fully integrated pixel with both color selectivity and photocurrent gain.

Chapter 2 will focus on the design of the integrated color filter. The section first introduces surface plasmons in general and shifts the discussion towards surface plasmons in gratings. This section discusses some of the interference effects used to design the photodetector for red, green, or blue sensitivity.

Chapter 3 will first give a brief overview of various photodetectors with a special emphasis on photoconductors with gain. The section initially begins with a derivation of the electrical characteristics of a single Schottky junction and examines the effect of placing two Schottky junctions back-to-back. The section then analyzes the effect of illuminating a MSM photodetector and concludes by briefly discussing mechanisms that can result in photocurrent gain in MSM photodetectors.

Chapter 4 presents a fabricated device with both color selectivity and photocurrent gain. The section presents the fabrication processes used to make the device and shows that the photodetector substantially improves photodetector performance.
Chapter 2

Plasmon-Based Integrated Filters

Figure 2.1 Localized surface plasmon resonance of a metallic nanoparticle.

Plasmons are coherent charge-density oscillations of conduction-band electrons. Interest in plasmonics has grown rapidly in recent years and new devices and structures have found many interesting applications in nanophotonics, photocatalysis, energy harvesting, and biomedicine. This broad applicability is a direct result of the ability of
surface plasmons to couple with incident light and convert light into nanoscale volumes below the diffraction limit.

Less explored is integrating surface plasmons directly with complimentary metal-oxide-semiconductor (CMOS) fabrication process. Until recently, the bulk of the literature has focused on silver and gold as plasmonic materials, due to their stability, ease of fabrication, and relatively low losses over a broad spectrum. In the visible regime, the dominant choice of plasmonic materials is silver since gold becomes lossy for wavelengths below 500nm. However, neither gold nor silver are compatible with CMOS processes, limiting their ultimate manufacturability. Recent progress in aluminum as a plasmonic material has shown that aluminum possesses exceptional optical properties in the visible and the ultra-violet. In addition, aluminum can exhibit strongly enhanced local fields due to its low screening, resulting in further photocurrent enhancements.

2.1. Grating structures

Plasmonic gratings offer an attractive route towards fully integrated, spectrally sensitive detectors and have been extensively used as tunable optical band-pass filters. Plasmonic gratings utilize the interference effects of surface plasmons to tune the center wavelength and shape of transmission windows. Recent work in plasmonic imaging devices has focused on optimizing the spectral response and design of silver plasmonic color filters. However, silver is not compatible with complementary metal-oxide semiconductor (CMOS) fabrication processes.
Aluminum color filters has shown full color tunability but the focus on the spectral properties of the filter has taken a far-field approach, with the filter placed hundreds of nanometers or microns above the photosensitive element.\textsuperscript{27-33}

![Plasmon dispersion curve and photon dispersion curve](image)

**Figure 2.2** Plasmon dispersion curve and photon dispersion curve. The momentum mismatch between the plasmon and the photon is $\Delta k$.

The spectral response of plasmonic gratings is determined by the spacing, or pitch, of the subwavelength grating slits.\textsuperscript{19, 21} The energy-momentum mismatch between a free-space photon and a surface plasmon reduces the efficiency of the conversion from photon to surface plasmon.\textsuperscript{34} A grating structure provides an additional momentum that allows incident light to overcome the momentum mismatch and couple more efficiently to incident light. The momentum provided by the grating is given by:\textsuperscript{34}
where $d$ is the distance between two adjacent subwavelength slits. The overall momentum for the surface plasmon of a grating illuminated at normal incidence and the $n$th grating mode is:

$$k_{sp} = k_{\text{incident}} + k_{\text{grating}} = k_0 + n \cdot \frac{2\pi}{d}$$  \hspace{1cm} (2-2)$$

Plasmonic nanostructures have also demonstrated photocurrent enhancement through strong field enhancements.\textsuperscript{35-37} For metals with low screening, like aluminum, the local fields can be increased dramatically.$^{11}$ This increased field enhancement decays evanescently, resulting in an additional photocurrent enhancement.

This thesis improves upon these previous integrated color filters and imaging sensors by integrating a plasmonic color filter with an imaging sensor with gain. The imaging sensor response is further enhanced by the strong local fields of the aluminum plasmonic grating and produces a large photocurrent response even in low-light conditions.
Silicon-based photodetectors rely on the creation of electron-hole pairs during the absorption process to convert incident photons into a measurable electrical current. For photodetectors without gain, holes and electrons are collected and one photon results in equivalent electron of current. In other words, the collection rate of photogenerated carriers is equivalent to the generation rate of the carriers. In materials that exhibit photocurrent gain, photogenerated carriers are collected at a much slower rate than the generation rate. This occurs either through avalanching or charge trapping. By trapping charges, the collection of carriers is delayed relative to the generation rate so > 1 electron of electrical current is created per absorbed photon. This effect has been demonstrated in photoconductors, where trap sites delay the collection of either electrons or holes, and in phototransistors, where a potential well is formed by two back-to-back pn
junction diodes. A schematic of the charge trapping in a photoconductor and phototransistor is presented in Figure 3.1.

![Diagram]

**Figure 3.1** a) Band diagram of photoconductor with photoconductive gain *via* electron trapping. b) Band diagram of a phototransistor, where charge is trapped in a potential well formed by two back-to-back pn junction diodes.

Photocurrent gain arises whenever the generation rate exceeds the transit time of generated photo-carriers. In general, the gain can be written as:\(^{38,39}\)
Gain = \frac{\tau}{\tau_t} \quad (3-1)

where \( \tau \) is the generation rate of photocarriers, and \( \tau_t \) is the transit rate. For high photocurrent gain, it is important to minimize the transit rate relative to the generation rate. This can be accomplished by trapping either holes or electrons and delaying the collection of photogenerated carriers for as long as possible. For telecommunications systems, gain is undesirable because trapping charges slows the transport of carriers, resulting in slower device speeds. For imaging applications, where speed is less of a premium, photocurrent gain can be used as an advantage.

Metal-semiconductor-metal photodetectors have been used extensively in ultrafast telecommunication systems due to their high speed, low noise, and ease of fabrication in CMOS processes.\(^{42-46}\) MSM photodetectors have been reported with switching times <20ps but at these high speeds, MSM photodetectors typically exhibit low responsivities and no photocurrent gain.\(^{47}\) At lower speeds (<5GHz), MSM photodetectors have been shown to exhibit photocurrent gain due to charge accumulation and barrier force lowering.\(^{48-52}\) For imaging applications with slower speed requirements, an MSM photodetector with an integrated color filter is a good candidate sensor for future imaging applications.

To understand the device presented in this thesis, it is important to understand how the device operates under dark conditions and analyze how the
device current responds to an applied voltage bias. These can be derived from analyzing the band structure and thermionic emission theory.

3.1. Schottky Band Structure

First, we derive the current-voltage characteristics of a single aluminum-silicon Schottky junction using thermionic emission theory. Thermionic emission theory is used to account for carrier emission due to fields, thermal energy, and illumination. The structure, shown in Figure 3.2, is an aluminum-silicon Schottky junction.
Figure 3.2 Aluminum-silicon Schottky Interface. $\chi_m$ is the metal work function, $\chi_s$ is the semiconductor work function, $E_c$ is the conduction band, $E_F$ is the Fermi energy, $E_v$ is the valence band, and $\phi_b$ is the Schottky barrier height.

For a dark structure, the carrier concentrations are derived from summing the drift and diffusion currents using the continuity equations:\textsuperscript{38,53}

\[ J_n = q\mu_n nE + \frac{qD_n dn}{dx} = \mu_n n \frac{dE_F}{dx} \]  \hspace{1cm} (3-2)

\[ J_p = q\mu_p pE - \frac{qD_p dp}{dx} = \mu_p p \frac{dE_F}{dx} \]  \hspace{1cm} (3-3)

\[ \frac{dn}{dt} = \frac{1}{q} \frac{dJ_n}{dx} - U + G \]  \hspace{1cm} (3-4)

\[ \frac{dp}{dt} = -\frac{1}{q} \frac{dJ_p}{dx} - U + G \]  \hspace{1cm} (3-5)

where $J_{n,p}$ are the current densities, $q$ is the electron charge, $n$ and $p$ are the carrier concentrations, $D_{n,p}$ are diffusion constants, $G$ is the generation rate, and $\mu_{n,p}$ are the electron and hole mobilities respectively; $E_{Fp}$ and $E_{Fn}$ are quasi-Fermi levels. For an n-type Schottky junction, the carrier concentration is orders of magnitude higher than for holes, so the electron current dominates over the hole current. In addition, the generation term $G$ is 0 for a dark Schottky diode. This simplifies the analysis for a single Schottky junction.

By solving equations (3-2) through (3-5), and taking into account the carrier distributions near the junction, it can be shown that the IV relation is given by:\textsuperscript{53}
Where \( A \) is the modified Richardson constant, \( T \) is the temperature, \( n \) is an ideality factor, \( V \) is the voltage across the junction and other constants as before in the continuity equations. It is important to note that a single Schottky junction does not exhibit photocurrent gain, since it is always possible to collect both carriers either through the Schottky barrier or through an ohmic contact. Under illumination, the generation term \( G \) becomes non-zero.

### 3.2. Photocurrent Gain

In the case of metal-semiconductor-metal devices, the two junctions form two back-to-back Schottky diodes. Since there are barriers at both junctions, the two diodes effectively form a potential well, which can then be used to trap charges and induce photocurrent gain, as in Figure 3.3.

![Diagram of a potential well with charge trapping](image)
Figure 3.3 Band diagram of a metal-semiconductor-metal photodetector under illumination. Photogenerated carriers are trapped in the potential well formed by two back-to-back Schottky junctions.

One major difference between a single Schottky junction and a MSM device is that the minority carrier concentration can no longer be ignored. By repeating the analysis as before, the IV characteristics for an MSM device is given by:

\[
J = AT^2 \left( e^{-\frac{q\phi_{bn}}{kT}} + e^{-\frac{q\phi_{bp}}{kT}} \right) \left( \sinh \frac{qV}{nkT} \right) \tag{3-7}
\]

where \( \phi_{bn} \) and \( \phi_{bp} \) are the n and p Schottky barrier heights. In an MSM device, one junction is guaranteed to be reverse-biased, while one is guaranteed to be in forward bias. Since the reverse biased junction has a higher impedance than the forward biased junction, the reverse-biased minority carrier emission current is the dominate current in an MSM photodiode. \(^{54,55}\)

Under illumination, the carrier densities are modified by an increase in the number of holes and electrons. For an n-type MSM photodetector, an applied electrical bias causes holes to migrate to the reverse-biased junction and electrons to the forward-biased junction, as in Figure 3.2. Since the electrons cannot be collected directly over the reverse-biased junction, they will accumulate in a potential well near the junction. This accumulation of holes leads to a strong image charge at the interface, which leads to image force lowering of the Schottky barrier and a subsequent increase in carrier emission at the junction.\(^{48-52}\)
Figure 3.4 Schematic of charge carriers in an MSM photodetector under bias. The uncollected electrons generated accumulate at the forward-biased junction (right).

Image force lowering reduces the Schottky barrier height, as shown in Figure 3.5. From equation (3-7), a lowering of the Schottky barrier leads to an exponential increase in the current flowing through the device. This occurs because accumulated charges at the Schottky junction electrostatically attract an image charge. This image charge creates a region of high electric field, which increases the momentum of carriers at the junction. This increases the number of carriers with enough energy and momentum to cross the Schottky junction, leading to an increase in the total current through the MSM device. The height of the barrier lowering has been found to depend on the electric field at the Schottky interface:\(^{53}\)

\[
\Delta \phi = \sqrt{\frac{qE_{\text{max}}}{4\pi\epsilon}} \quad (3-8)
\]
where $E_{\text{max}}$ is the maximum electric field, $q$ is the electronic charge, and $\epsilon$ is the dielectric of the semiconductor. For context, a modification of the barrier height, $\Delta \phi$, by 0.119 V results in a 100X increase in the current. The electric field can be extremely high because the separation between the charge and its image charge can be small (~1 nm).

Figure 3.5 Schematic demonstrating Schottky barrier lowering via image charges. The lowered barrier (black) allows exponentially more charge carriers to cross the Schottky interface than the unlowered barrier (gray).
Chapter 4

Color-Sensitive Imager with Photocurrent Gain

4.1. Introduction

This thesis improves upon current technology by combining a plasmonic color filter with a photodetector that exhibits gain. Aluminum color filters has shown full color tunability but the focus on the spectral properties of the filter has taken a far-field approach, with the filter placed hundreds of nanometers or microns above the photosensitive element.\textsuperscript{27-33} We build on recent progress in aluminum plasmonics to demonstrate a color-sensitive, CMOS-compatible photodetector. The photodetector is a metal-semiconductor-metal (MSM) photodetector that exhibits photocurrent gain and uses thin film and plasmonic interference effects for narrowband wavelength selectivity and photocurrent enhancement.
The device presented, shown schematically in Figure 4.1a, is a MSM photodetector with an integrated color filter composed of a 50 nm aluminum grating, a 50 nm oxide layer, al-Si Schottky junctions, on a p-type silicon substrate. The oxide serves to electrically passivate the silicon and as an optical spacer for the aluminum grating. From simulations, optical spacers thinner than 15nm significantly dampen and red-shift the spectral response of the grating. Our simulations corroborate other studies in the literature, where an optical spacer thickness between 30nm and 100nm has been found to be optimal for near-field coupling between silicon and metallic nanostructures.\textsuperscript{56, 57} The aluminum grating filters the input light and provides an additional photocurrent enhancement due to strong, localized field enhancements.

**4.2. Sensor fabrication and optical response**

A schematic of the fabrication process flow is shown in Figure 4.1b. The device is fabricated using standard cleanroom fabrication techniques. The starting substrate is a lightly doped (10-30 $\Omega$/cm) <100> p-type silicon wafer (Silicon Valley Microelectronics). The substrate is initially protected by a thermally grown 100 nm oxide layer but thinned to 50nm by reactive ion etching (RIE, Trion) for 100 s. The etch parameters result in an oxide etch rate of $\sim0.5$ nm/s. The etch rates and oxide thicknesses were verified using ellipsometry (Horiba Jobin Yvon). After thinning the oxide, the samples are cleaned by sonicating in acetone for 5 minutes, rinsing in isopropyl alcohol (IPA), and blow drying with dry nitrogen gas. The aluminum-silicon Schottky junctions, measuring 10 $\mu$m by 10 $\mu$m, are formed \textit{via}
photolithography. A photoresist (Shipley, S1813) is spin-coated on the chip and exposed for 5 s (Karl Suss). The resist is developed (Microchem, MF319) for 60 s and dry etched for 100 s to open up contact areas. The chip is immediately transferred to an electron-beam evaporation chamber (Semicore). The overall exposure time to atmosphere is less than 5 minutes, to minimize oxidation at the silicon-aluminum interface. A 100 nm aluminum layer is deposited at 0.7 Å/s at a base pressure of 5.0e-7 Torr. The aluminum deposition is followed by a gold deposition of 100 nm. The gold layer is used for alignment marks in a subsequent electron-beam lithography step and do not affect the electrical properties of the photodetector. The excess metal and photoresist is removed by soaking in acetone at room temperature for 15 minutes and rinsing in IPA. The gratings, measuring 7 μm by 15 μm, are fabricated using electron beam lithography. The grating slits are maintained at a constant 100 nm by 5 μm long for all photodetectors. The color detection window of the photodetector is tuned by increasing or decreasing the pitch distance between the slits. From simulations, a slit pitch of 300 nm is optimal for blue light, 400 nm for green light, and 500 nm for red light. The e-beam resist (Microchem, PMMA A4) is developed for 50 s in a 3:1 solution of IPA:methyl isobutyl ketone (MIBK, Microchem). Liftoff is performed by soaking in acetone at ambient for 15 minutes and rinsing in IPA. A scanning electron microscope (SEM) image of a completed device is shown in Figure 4.1c.
Figure 4.1(a) Schematic of the metal-semiconductor-metal (MSM) photodetector. The device is comprised of a 50 nm oxide layer, a 50 nm thick aluminum grating, and two Al-Si Schottky junctions. The oxide layer serves as electrical passivation and as an optical spacer. The aluminum grating is used for spectral selectivity. (b) The fabrication process flow for the photodetector. The contacts are defined via photolithography and the grating is fabricated using electron beam lithography. (c) Scanning electron microscope (SEM) image of a fabricated device. The image is taken at 45° tilt angle. The device has a slit pitch of 500 nm. Each slit is 100 nm wide and 5 μm long. The aluminum grating is 7 μm by 15 μm.

4.3. Optoelectric Response

The spectral response is shown in Figure 4.2. Red, green, and blue photodetectors, shown in Figure 4.2a-c, were fabricated with grating pitches of 500 nm, 400 nm, and 300 nm, respectively. The measured responsivities are shown in
Figure 2d. The full-width-at-half-maximum (FWHM) is \(~90\) nm for the blue detector, \(~100\) nm for the green detector, and \(~115\) nm for the red detector. The experimentally obtained responsivity (Figure 4.2d) closely matches the theory (Figure 4.2e). The asymmetric spectral response arises from the interference between incident light and light scattered by the photodetector. For light with frequencies below the interference resonance, constructive interference occurs (Figure 4.2f) and the photodetector preferentially absorbs light. Conversely, light above the resonance frequency destructively interferes and the detector preferentially reflects light (Figure 4.2g).\(^{56}\) During constructive interference, the high field enhancements of the plasmonic filter increase the in-coupling cross-section, resulting in additional photocurrent enhancement.\(^{56}\) By varying the oxide thickness, the interference resonance can be tuned near the plasmonic grating resonance, simultaneously improving the spectral selectivity and photocurrent output.
Figure 4.2 (a) – (c) SEM images of the fabricated gratings for pitch distances of 500nm (red), 400nm (green), and 300nm (blue), respectively. Images were taken at 45° tilt angle and spaced 35 μm apart. (d) Measured responsivity for the red, green, and blue photodetectors. (e) Calculated power absorbed in the silicon. (f) Time-averaged electric field enhancement plots of the device at maximal absorption and (g) minimal absorption.
4.4. Gain Mechanism

It is important to note that the responsivity of the photodetectors exceeds 1 A/W, which is partially due to the near-field enhancement. We measure a maximum responsivity of 12.54 A/W for the blue detector, 12.07 A/W for the green detector, and 11.18 A/W for the red detector. From Figure 4.2f, a volume averaged electric field enhancement of ~2.5 should result in a photocurrent enhancement of ~30%. Even for a 100% quantum efficiency photodiode, the maximum responsivity is 1.3 A/W, which strongly indicates that the photodetector has an additional photocurrent gain mechanism.

To better understand the photocurrent response and gain of this device, we characterized the photodetector in two different operating regimes, with and without photocurrent gain. Representative current-voltage (I-V) curves for a dark and illuminated MSM photodetector is shown in Figure 4.3a. The device was illuminated on-resonance at 560 nm with 600 nW incident power. The extracted barrier height is 0.37 V with an ideality factor of 1.12, which agrees with literature reported values of aluminum-p-type silicon Schottky junctions. The asymmetry in the I-V curves is due to different amounts of oxidation at the aluminum-silicon interfaces. It is well known that the electrical characteristics of Schottky junctions are extremely sensitive to interfacial oxidation. The photodetector produces a photocurrent of 4.6 μA at 3 V bias, corresponding to a responsivity of 7.67 A/W. The MSM photodetector exhibits two operating regimes: the active regime (white), and the linear regime (gray). In the active regime, generated electrons are swept to the
forward-biased junction and holes swept to the reverse-biased junction. Since there are potential barriers at both junctions, not all carriers are immediately collected. The uncollected carriers accumulate in the potential well between the junctions, which lower the Schottky barrier and induce photocurrent gain. In lightly-doped substrates, the long carrier lifetimes (~100 μs)\textsuperscript{58, 59} ensure that photo-generated carriers can accumulate without recombining, allowing for large photocurrent gains.
In the linear regime, the photodetector acts as a photoconductor, which gives a direct measure of the photogenerated carrier densities without gain. The I-V curves (Figure 4.3b) show linear responses in the +/- 100 mV range before becoming more exponential. The conductances of the curves are extracted and plotted in Figure 4.3c. The device shows linear increases to the device conductance for linear increases in incident power. This linear response suggests that the greater-than-unity responsivity is an intrinsic device gain, rather than other gain mechanisms such as carrier multiplication, which would depend quadratically on the incident power. The slope of the change in the conductance gives a direct measure of the quantum efficiency by the relation:

$$\Delta \sigma = q(\mu_n + \mu_p) \cdot \Phi \eta$$  \hspace{1cm} (4-1)$$

where $\Delta \sigma$ is the change in conductance, $q$ is the electric charge, $\mu_n$ and $\mu_p$ are the electron and hole mobilities, respectively, $\Phi$ is the photon flux, and $\eta$ is the quantum
efficiency. The electron mobilities were estimated based on the chip resistivity of 16 Ω/cm and literature values for mobilities based on known doping concentrations.\textsuperscript{60, 61} The calculated quantum efficiency is 5.8\%, which corresponds to a photocurrent responsivity of 26.2 mA/W. In comparison, the photodetector in the active regime has a responsivity of 7.67 A/W. This result suggests that the total intrinsic device gain due to near-field photocurrent enhancement and barrier lowering is greater than 290.
An important metric for photodetectors is the minimum detectable signal. For the device presented, the photodetector exhibits a dark shunt resistance of 5.96 GΩ and a dark leakage current of 2.05 nA. The Johnson noise spectral density is estimated from \((4k_BT B/R)^{1/2}\) to be 1.64 fA Hz\(^{-1/2}\). The shot noise limit is determined from \((2qI_dB)^{1/2}\) to be 0.24 fA Hz\(^{-1/2}\), where \(k_B\) is Boltzmann’s constant, \(T\) is the temperature, \(B\) is the noise bandwidth, \(R\) is the detector dark resistance, \(q\) is the electron charge, and \(I_d\) is the dark current. The calculated minimum detectable signal, or noise-equivalent power (NEP), is 1.66 fW Hz\(^{-1/2}\), in agreement with other silicon detectors.\(^{38}\)

To contextualize the device performance, we compare the device responsivity to other photodetectors and color filters in the literature. The device presented shows 2 orders of magnitude better responsivity than typical MSM photodetectors used in telecommunications, due to the enhanced absorption and
photocurrent gain. However, the photocurrent gain due to charge accumulation places an upper limit on the operating speed of the device. The unity-gain photocurrent bandwidth of a MSM photodetector is given by:

\[ B = \frac{\pi \mu V_{th}}{2L^2} \]

where \( B \) is the bandwidth, \( L \) is the distance between the junctions, \( \mu \) is the mobility, and \( V_{th} \) is the threshold voltage. For the device presented, \( V_{th} = 0.36 \) V, \( L = 20 \) \( \mu \)m and \( \mu \) is estimated to be 500 cm\(^2\)/(V\cdot s), resulting in a bandwidth of 6.9 GHz. In terms of spectral sensitivity, this device shows equal or better performance than previously reported plasmonic color filters. The FWHM spectral selectivity is <120 nm for all colors while other reported aluminum color filters have FWHM of at least 110 nm, and many filters with FWHM >200 nm. Silicon photoconductors have substantially higher responsivities (>10\(^5\) A/W), but much slower speeds (~MHz) and significantly higher noise levels (~1 \( \mu \)W NEP). Phototransistors also exhibit high photocurrent gain (> 100) but suffer from slow speeds (< 1 MHz) and high noise levels (~1 nW Hz\(^{-1/2}\) NEP). Silicon nanowires and quantum dot detectors have also been shown to have high responsivities and photocurrent gain but at slow speeds (~KHz). Graphene-based detectors with broadband absorption, high speed, and low noise have been demonstrated, but suffer from low responsivities (~mA/W). In terms of device tradeoffs between speed, responsivity, and color sensitivity, the device presented in this letter demonstrates, to our knowledge, one of the best device performances to date.
We have demonstrated a high-performance MSM photodetector that utilizes charge accumulation for photocurrent gain and an integrated Al plasmonic filter for spectral sensitivity. The detector makes use of near-field and thin-film interference effects to enhance the absorption and to create a narrowband spectral response. We believe this work will lead to broad impacts in the design and integration of Al plasmonic color filters in future CMOS-compatible imaging systems and photodetectors. Further engineering of the interference effects of the optical near-field and the underlying substrate could have broad impacts on the design and fabrication of color displays, novel imaging sensors, and new devices for ultrafast optical communications technologies.
References


