An improved wire grid polarizer for thermal infrared applications

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ABSTRACT

Moxtek has developed a high contrast IR polarizer on silicon suitable for long wavelength thermal IR applications using our aluminum nanowire, large area patterning capabilities. Between 7 and 15 microns, our 144 nm pitch polarizers transmit better than 70% of the passing polarization state and have a contrast ratio better than 40 dB. Transmission and reflectance measurements were made using a Fourier Transform Infrared (FTIR) spectrometer with instrument accuracy verified using silicon and germanium reference standards. Results were compared to RCWA modeling of the wire grid polarizer (WGP) performance on antireflection-coated wafers. The FTIR instrument noise floor limited the maximum contrast measurement to about 40 dB, but high polarizer contrast was verified at 10.6 μm using a CO_2 laser and pyroelectric detector. A continuous wave Gaussian beam from a CO_2 laser was used for Laser Damage Threshold (LDT) testing and showed LDT values of 110 kW/cm^2 and 10 kW/cm^2 in the blocking and passing states respectively. Analysis of laser damage threshold test samples shows the damage propagating from defects in the anti-reflection (AR) coating. Removing these AR coating defects should improve LDT performance and transmission in the thermal IR.

Keywords: wire grid polarizer, nanofabrication, sub-wavelength optics, form birefringence, laser damage threshold, MWIR, LWIR, thermal IR

1. INTRODUCTION

The ubiquitous wire grid polarizer remains one of the most useful optical components in the field. Widely used in applications such as displays, imaging, sensors, communications, and scientific instrumentation, the wire grid polarizer (WGP) typically consists of an array of metallic lines with sub-wavelength pitch supported by a transparent substrate. Wire grid structures are known to be effective as infrared polarizers with short optical path and large acceptance angles.[1-2] Existing WGP products designed for long wavelength thermal IR applications typically suffer from low contrast (≤350) between transmission of linearly polarized light in the passing and blocking configurations, which is due to their relatively large wire grid pitch (typically ≥ 370 nm). Moxtek and others have previously demonstrated a dramatic increase in aluminum WGP contrast at visible and ultraviolet wavelengths by reducing the pitch.[3-4] We postulated that a dramatic reduction in pitch from that found in typical IR WGP products should greatly improve mid- and long-wavelength IR contrast. Moxtek has therefore developed several high contrast IR polarizers on anti-reflection (AR) coated silicon suitable for mid-wavelength IR (MWIR) and long-wavelength IR (LWIR) applications using our aluminum nanowire, large area patterning capabilities. Moxtek's MWIR polarizer transmits better than 95% of the passing state between 3.3 and 5.7 microns while maintaining a contrast ratio of better than 35dB from 3-7 microns. The Moxtek LWIR polarizer transmits better than 70% of the passing polarization state between 7 and 15 microns and has a contrast ratio exceeding 40 dB. Potential applications for the Moxtek MWIR and LWIR polarizers include spectroscopic measurement systems, optical isolators for industrial lasers, and polarization sensitive imaging systems for hyperspectral imaging, guided missile technology, and forward-looking infrared thermal imaging.

With the increasing use of lasers in polarization-sensitive industrial and scientific applications, Moxtek has pursued laser damage threshold (LDT) testing in both the passing and blocking polarizer configurations. Preliminary testing and analysis indicate that defects introduced during silicon AR coating are currently limiting the LDT performance in our broadband LWIR product. The MWIR polarizer uses an improved AR coating and does not show the same damage initiation mechanism. Figure 1 depicts the schematic and electron beam images of the Moxtek aluminum wire grid polarizer on silicon, as well as an image demonstrating our wafer-scale processing capability. The AR coatings can be custom designed to provide enhanced transmission for narrowband or broadband applications. The fine pitch (144 nm) and large rib aspect ratio (> 3:1) provide for improved transmission and dramatically higher contrast than competing products.

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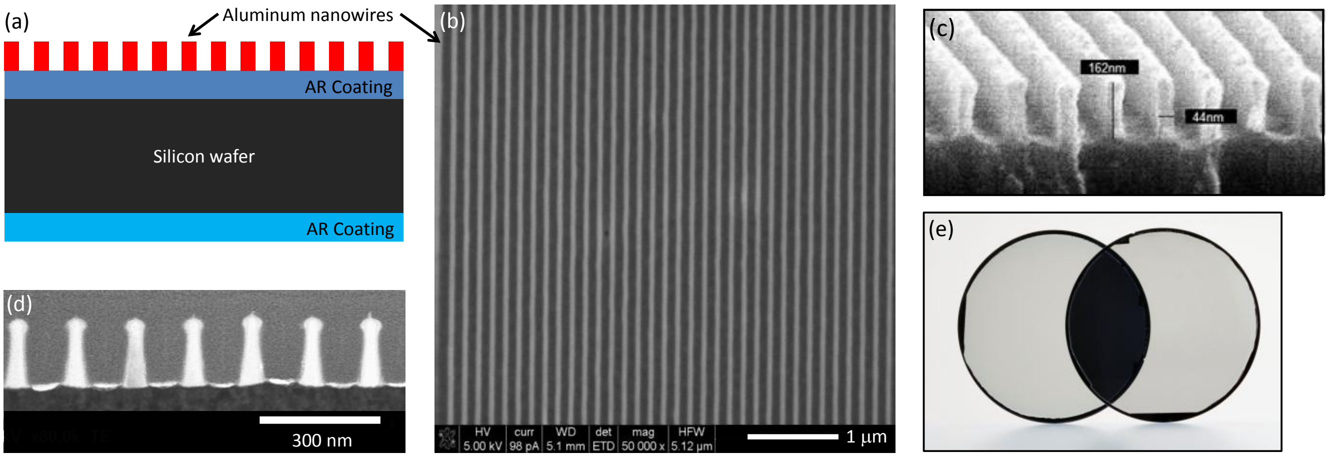


Figure 1. Moxtek Wire Grid Polarizers. (a) Schematic of wafer cross section (not to scale). (b)-(c) SEM images of aluminum wires on MWIR AR-coated silicon in (b) Plan view and (c) cross-section. (d) STEM image of rib cross section for LWIR product after embedding in Platinum and FIB milling to remove a thin section for imaging. (e) Photograph of crossed 144 nm pitch aluminum nanowire grid polarizers on 200 mm diameter glass wafers, depicting Moxtek wafer scale processing capabilities.

2. METHODOLOGY

2.1 Overview

FTIR analysis of part performance in transmission was completed at Moxtek and verified at an outside reference lab. A silicon reference standard was used to validate instrument accuracy for transmission measurements of the passing polarization state and compared with transmission results at a fixed wavelength using a CO_2 laser centered at 10.6 µm. Laser Damage Threshold measurements were also completed in the passing and blocking polarizer orientations. FTIR analysis of part performance in reflectance was completed at an outside reference lab using an absolute specular reflectance accessory. A germanium reflectance reference standard was used to validate instrument accuracy for reflectance measurements. Optical modeling of part performance was undertaken using the rigorous coupled wave analysis (RCWA). Sample analysis was performed using scanning electron microscopy (SEM), focused ion beam (FIB) milling, and scanning transmission electron microscopy (STEM).

2.2 FTIR transmission experiments

A Cary 670 FTIR spectrometer from Agilent was used for normal incidence transmission measurements at Moxtek using a fixed pre-analyzer consisting of two Moxtek polarizers on silicon spaced by several millimeters, and containing the same double-sided AR coatings as the product being measured. After nitrogen purging for 5-10 minutes, a background scan was taken without a sample in the compartment to establish the 100% transmittance baseline. The product sample was then placed on a rotary stage and the broadband FTIR interferogram signal minimized to establish the blocking state polarizer orientation. After purging and measurement of the blocking state transmittance, the sample was rotated 90° and re-purged before recording the passing state transmittance. The sample was then removed and the purged background re-measured to ensure minimal baseline drift in the single beam FTIR instrument. Blocking the beam with a metal plate established the noise floor. To ensure ordinate accuracy in the intermediate transmission ranges, a bare (uncoated) silicon reference sample was also scanned and compared to transmittance models generated from IR variable angle spectroscopic ellipsometry (IR-VASE) analysis performed by the J.A. Woollam Company. The transmission experiments were also repeated at Ball Aerospace's Optical Testing Facility using a Nexus 870 FT-IR ESP spectrometer from Thermo Nicolet and showed the same nominal behavior in the passing state and blocking states. 256 scans were averaged per spectra in the blocking polarizer configuration to achieve sufficient dynamic range to measure a 10,000 contrast ratio with 5:1 signal to noise ratio. Figure 2 depicts the FTIR sample chamber and the experimental setup for transmission measurements.

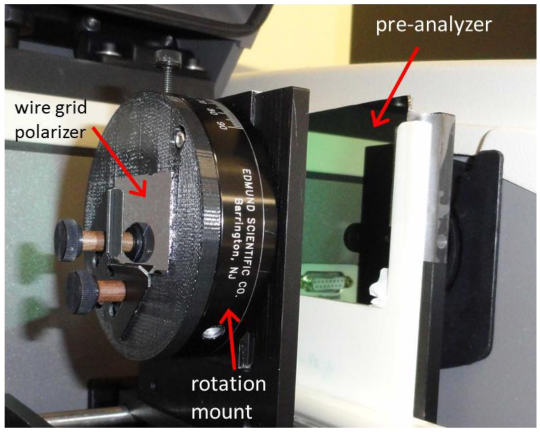


Figure 2. Transmission measurement setup for FTIR spectroscopy. The pre-analyzer (a doubled Moxtek AR-coated product) is held at a fixed position which defines the orientation of the transmitted polarized light. The reference scan is taken after purging the chamber (without a sample). The rotation mount allows for fine alignment of a wire grid polarizer sample to the pre-analyzer by nulling the infrared interferogram. The blocking measurement is taken after purging with nitrogen and then the part is rotated 90° to measure the passing orientation.

2.3 FTIR reflection experiments

12° and 45° angle of incidence (AOI) absolute reflectance experiments were also performed at Ball Aerospace's Optical Testing Facility using the same Thermo Nicolet FTIR spectrometer and a Harrick absolute specular reflectance accessory with a broadband Harrick WGP on KRS-5 substrate as the pre-analyzer. The normal to the plane of incidence defined by the incoming and reflected beams was oriented parallel to the wires. A nitrogen-purged baseline was taken in the "V" beam path configuration and the sample was then added and the kinematic mount flipped to generate the "W" beam path configuration (two bounces off sample) for measurement of the square of the sample reflectance. The sample was then removed and the pre-analyzer rotated 90° for another baseline in the "V" configuration followed by sample reflectance measurement of the orthogonally polarized state. The reflectance levels of the instrument were verified using an uncoated piece of double-side-polished silicon and a germanium IR specular reflectance standard from Middleton Research**.**

2.4 Laser damage threshold testing

For the broadband LWIR product, laser damage threshold testing was performed at a wavelength of 10.6 μm using a continuous wave Synrad Firestar CO_2 laser at Spica Technologies, Inc. The beam was focused using a convex ZnSe lens (1 meter focal length) to a 360 μm $1/e^2$ spot size with a Rayleigh length of approximately 2 mm. The beam profile was measured using a calibrated aperture approach. The polarization purity of the laser beam was improved using a thin film plate polarizer designed for 10.6 μm wavelength. The beam was steered using zero-phase reflector mirrors and the laser power was attenuated using the reflective thin film plate polarizer and a partial reflector. Fine-tuning of laser output power was achieved using RF carrier wave modulation. Operating the laser at low powers led to increased carrier wave modulation of the instantaneous laser power and LDT behavior approaching that of a pulsed laser experiment. The CO_2 laser was thus operated at high power to reduce the spikes in the beam fluence and more faithfully characterize the continuous wave LDT of the product. The samples were tested with the aluminum ribs facing the incoming laser beam. Images of the sample surface were recorded before and after laser exposure using a 100x reflective microscope with Nomarski objective and examined for signs of laser damage. Damage was also identified by monitoring the power passing through the LWIR polarizer using a Laser Precision Meter Rk-5720 Power Ratiometer with Laser Probe Rk-570 pyroelectric power head and integrated chopper. An Ophir 150C-sh thermopile detector head with SH-USBI interface was used to measure incident laser power.

2.5 Sample analysis

Samples were characterized in plan-view and cross-section by SEM. It was found that a further investigation of the cross-sections by STEM was needed for improved resolution of the finer-scale sample features. Cross sectional STEM lamellae were prepared by a focused ion beam (FIB) in-situ lift-out technique using an FEI Nova 200 Dual Beam instrument. Samples were then observed in bright and dark field using a Hitachi HD-2000 STEM instrument operating at 200 kV. Platinum infiltration was performed before the FIB milling to protect the delicate wire grid structure from beam damage.

2.6 Optical modeling

Rigorous Coupled Wave Analysis (GSolver® version 4.20b) was utilized in optical modeling of the silicon IR products. The model incorporated silicon IR optical constants generated by J.A. Woollam from IR-VASE and transmittance analysis of a series of uncoated silicon parts. The model also utilized aluminum optical constants derived from an earlier J.A. Woollam IR analysis based on a generic oscillator model. Vendor AR coating data was also input into the optical model to account for the reduced silicon reflectivity. For modeling purposes a simple rectangular wire cross section was assumed, with the metal duty cycle fixed at 35% (50.4 nm) of the wire grid pitch (144 nm). The wire height was set to 190 nm, giving an aspect ratio of almost 3.8 to 1. Up to 120 reflected and 120 transmitted diffracted orders were retained in the RCWA calculations, yet convergence was typically observed after the incorporation of only 20 reflected and 20 transmitted diffracted orders.

3. MEASUREMENT RESULTS AND DISCUSSION

3.1 Overview

FTIR transmission analysis of Moxtek IR polarizers showed excellent contrast results between blocking and passing states (>35 dB). For the MWIR product, passing state transmission was typically very high (>95%) over the AR-coating design region. AR-coating defects and silicon IR absorption limited the passing state transmission for the LWIR product to about 70-90% for the 7-15 μm design region. RCWA modeling results for normal incidence transmission of the LWIR polarizer match the general trends observed in the corresponding FTIR experiments.

For the broadband LWIR product, preliminary LDT testing indicates that damage is being initiated at defects introduced during silicon AR coating. The Moxtek MWIR polarizer has an improved AR coating and does not show the same damage initiation mechanism. In the blocking state, the LWIR product can withstand 110 kW/cm^2 of continuous wave CO_2 laser radiation at 10.6 micron wavelength, while the parts show an order of magnitude lower laser damage threshold in the passing polarization state.

3.2 FTIR transmission experiments

Figure 3 depicts FTIR measurement results of transmission for typical LWIR and MWIR products as well as the calculated contrast ratios. Transmission of the passing polarization state for the MWIR product is better than 95% between 3.3 and 5.7 μm, while the LWIR product transmits between 73 and 92% in the AR coating design region. The Moxtek LWIR broadband polarizer performance in the passing state is currently limited by the silicon substrate thickness (due to IR absorption features) and the AR coating performance. The FTIR instrument noise floor limited transmission measurement in the blocking state, but the maximum measurable contrast ratio was still better than 40 dB between 3 and 15 microns. The MWIR product maintained a contrast ratio of better than 35dB from 3-7 μm, while the LWIR product had an average contrast ratio of about 43.5 dB from 7-15 μm. High contrast for the LWIR product was verified at Spica Technologies using a CO_2 laser source and showed contrast ratios ranging from 40.5 to 48.1 dB at 10.6 μm wavelength with a typical contrast of about 45 dB.

3.3 FTIR reflection experiments

Figure 4 presents polarizer reflectance at 12° and 45° AOI in both in the passing (R_p) and blocking (R_s) configurations. The reflectance remains low for the passing state at large angles, which should increase system efficiency when projecting or imaging IR sources with a large acceptance angle. In imaging applications, a small f-number beam can be passed through these wire grid polarizers without a significant decrease in intensity towards the edges of the beam.

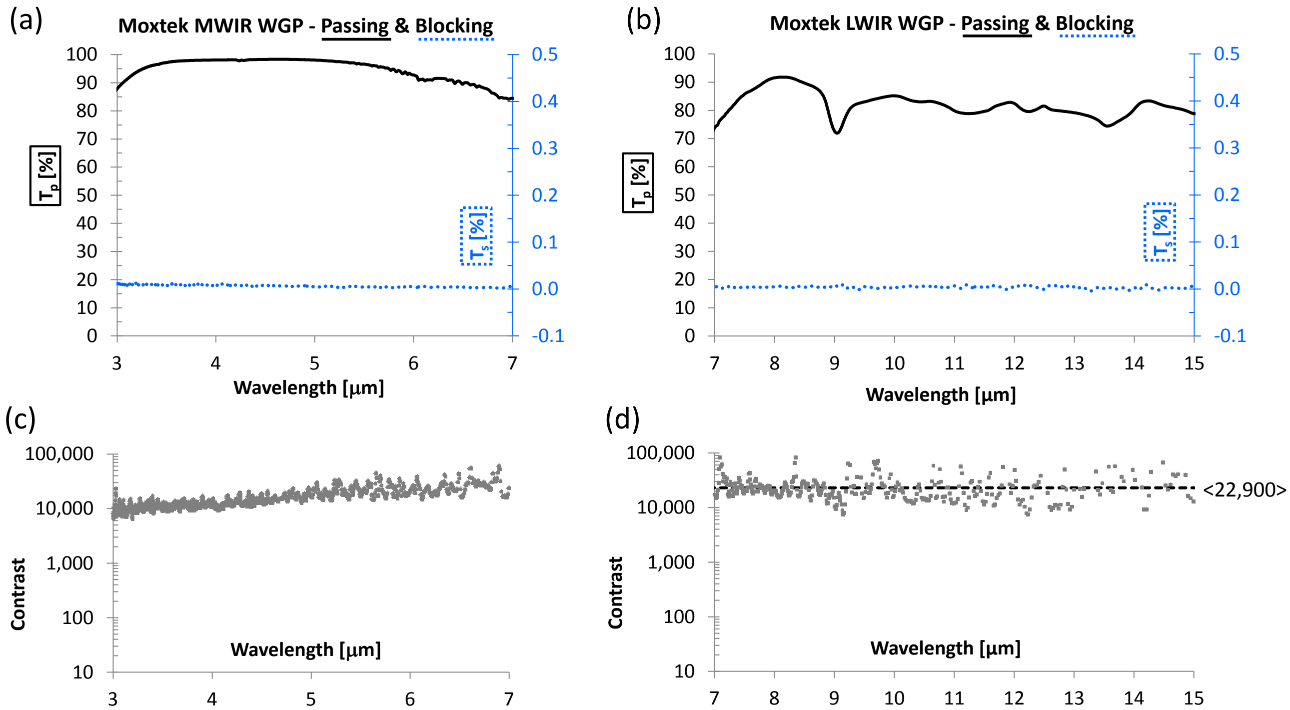


Figure 3. FTIR transmission measurement results for typical (a) MWIR and (b) LWIR products, as well as the corresponding contrast ratio (c) and (d) between passing and blocking states. In plots (a) and (b), the solid black lines denote the transmittance of *p*-polarized light and use the full transmittance scale on the left, while the dotted blue lines indicate *s*-polarized light and use the reduced ordinate scale on the right.

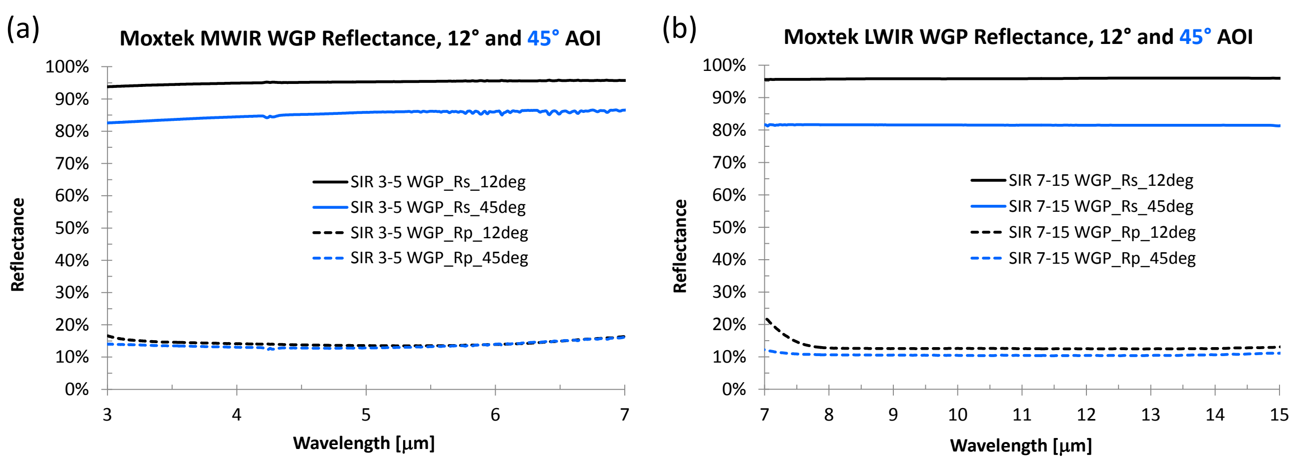


Figure 4. FTIR reflectance measurement results for (a) MWIR and (b) LWIR products. Solid and dashed lines denote reflectance of *s*- and *p*-polarized light respectively. Black and blue text indicate 12° and 45° Angle of Incidence (AOI) respectively.

3.4 Laser damage threshold testing

For the broadband LWIR product, preliminary laser damage threshold testing indicates that defects introduced during silicon AR coating are limiting performance. In the blocking state the wires can withstand 110 kW/cm^2 of continuous wave CO_2 laser radiation at 10.6 μm wavelength, while the parts show an order of magnitude lower laser damage threshold for the passing polarization state (10 kW/cm^2). The damage appears to initiate and spread from defects in the AR coating. The samples were tested with the aluminum wires facing the incoming laser beam, and hence in the blocking configuration the wire grid should help protect the AR coating defects from laser damage as they reflect over 95% of the incident radiation. The MWIR polarizer used an improved AR coating and did not show the same damage initiation mechanism.

3.5 Sample analysis

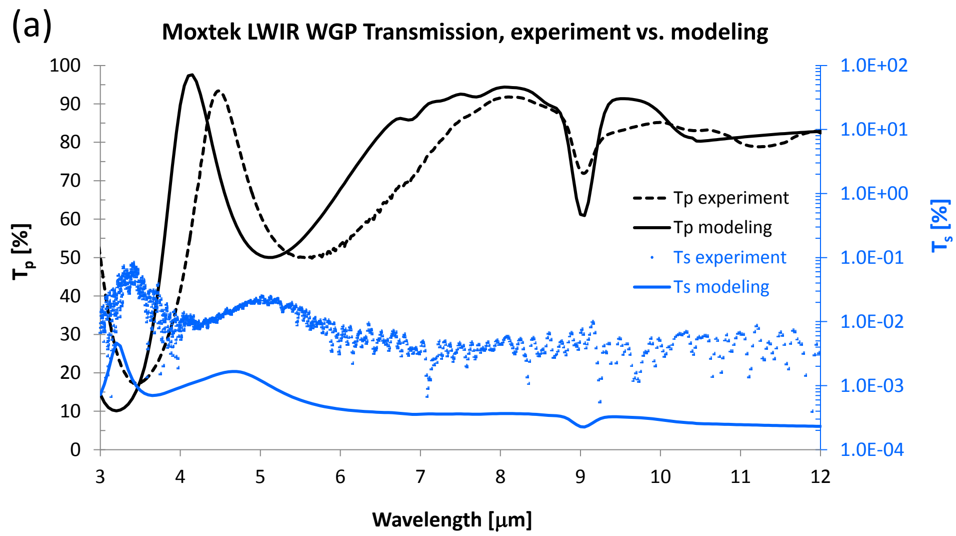
From SEM and STEM images (figures 1c and 1d), it is evident that the etched aluminum wires do not have the rectangular cross section assumed in the optical modeling. From the STEM analysis of the LWIR product, the wire height is about 190-200 nm and the wires are significantly narrower than the 50.4 nm that was assumed for the optical modeling. Hence the modeling significantly overestimates the metal duty cycle in the wire grid, which will affect the accuracy of the predicted transmission behavior and resulting contrast.

3.6 Optical modeling

To verify the accuracy of the optical modeling, the LWIR polarizer transmittance was plotted against the corresponding experimental data in figure 5a. The interference fringes appear at shorter wavelengths in the modeling, and although more pronounced, the absorption feature at 9 μm is well aligned to the experimental measurement. The transmission of the polarizer in the blocking state (labeled T_s) is predicted to be an order of magnitude smaller than what was found experimentally. Errors in the fit could be due to the use of improper optical data in the infrared, the omission of native oxides from the modeling,[2] or the use of improper thickness for one or more simulation layer. Geometrical parameters such as metal wire width and shape are also incorrectly defined in the model when compared to the SEM and STEM analysis results. The larger duty cycle assumed in the modeling will act to reflect and absorb more light when the polarizer is in the blocking configuration, which helps explains the reduced transmittance in the model vs. the experimental case. The shift towards shorter wavelengths in the interference fringes of the modeled transmission in figure 5a might be due to the use of improper IR optical constants and layer thicknesses for the AR coating or silicon substrate. The silicon optical constants used in the modeling were based on an analysis of double-side polished silicon performed by J.A. Woollam using coupled IR-VASE and transmission measurements, and had a slightly lower value of IR index of refraction than the value extrapolated from the well-cited analysis of Herzinger et.al.[5]

4. CONCLUSIONS

Moxtek has developed a high contrast IR polarizer on silicon suitable for long wavelength thermal IR applications using our aluminum nanowire, large area patterning capabilities. Between 7 and 15 μm, our 144 nm pitch LWIR polarizers transmit better than 70% of the passing polarization state and have a contrast ratio better than 40 dB. Transmission and reflectance measurements from a Fourier Transform Infrared spectrometer show qualitative agreement with optical modeling results from a rigorous coupled wave analysis package. Preliminary laser damage threshold (LDT) testing and sample analysis indicate that damage is initiated at defects in the silicon AR coating. In the blocking state, the wires can withstand 110 kW/cm^2 of continuous wave CO_2 laser radiation at 10.6 μm wavelength (360 μm spot size), while the parts show an order of magnitude lower laser damage threshold of the passing polarization state. Removing the AR coating defects should improve LDT performance in the thermal IR and may also result in an increased transmittance in the passing configuration. Moxtek has also developed a MWIR polarizer which shows high contrast (>35 dB) between blocking and passing states and an exceptionally high passing state transmission (>95% between 3.3 and 5.7 μm). The Moxtek MWIR polarizer has an improved AR coating and does not show the same LDT damage initiation mechanism.



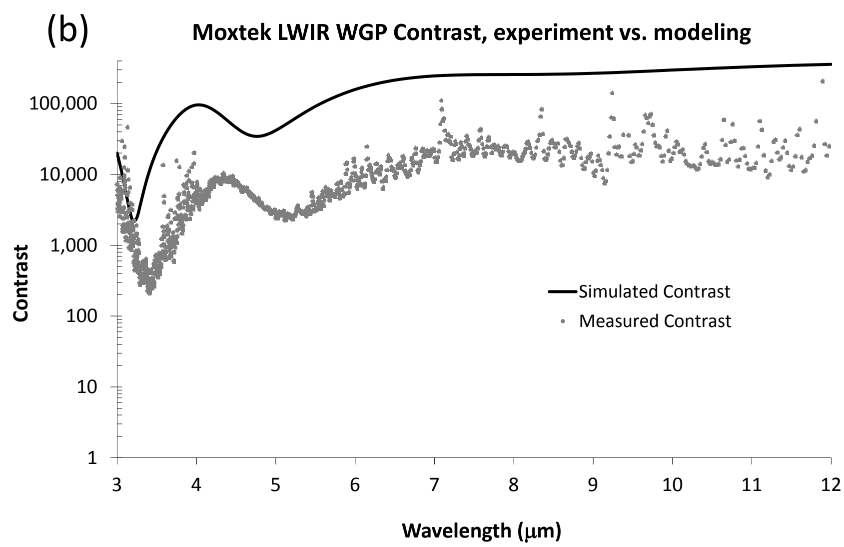


Figure 5. Comparison of optical modeling to FTIR measurements for (a) LWIR polarizer transmission and (b) contrast ratio.

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