Demonstration of distributed capacitance compensation in a metal-insulator-metal infrared rectenna incorporating a traveling-wave diode

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ABSTRACT

We experimentally demonstrate that the transmission line impedance of traveling-wave diodes can circumvent resistance-capacitance time-constant limitations of metal-insulator-metal diodes in rectennas operating at optical frequencies. We fabricated low resistance (380 Ω) and moderate responsivity (0.46 A/W) metal-insulator-metal traveling-wave diodes. When a rectenna incorporating the traveling-wave diode was illuminated with 10.6 μ m radiation, it produced a peak system responsivity of 130 μ A/W and a detectivity of 1.0 × 10⁴ Jones. These results agree with the simulated device performance and exceed the response of an equivalent lumped-element metal-insulator-metal rectenna.

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I. INTRODUCTION

Since optical rectennas were first proposed in the 1970s by Bailey,1 they have generated lots of interest for applications in energy harvesting and detection of infrared radiation. Optical rectennas consist of microscale antennas coupled to high speed diodes to collect and rectify infrared and visible radiation. Microwave rectennas can make use of semiconductor diodes and can operate at overall power conversion efficiencies up to 90%.² At optical frequencies however, semiconductor diodes are limited by their plasma frequency and electron mobility. Therefore, optical rectennas require an alternative ultrafast diode to operate in the infrared and beyond. One promising candidate is metal-insulator-metal (MIM) diodes, which use femtosecond fast electron tunneling³ through thin insulators for rectification.³⁻ However, a fast rectification mechanism is not the only requirement. Rectennas must have a diode and an antenna that are impedance matched with a sufficiently low RC time constant.^{8,9} Given the inherently capacitive structure of an MIM diode and the tradeoff between resistance and capacitance when its area is changed, the fundamental cut-off frequency of a lumped-element

MIM rectenna is in the low terahertz,⁸

$$f_{cutoff} = \frac{1}{2\pi RC}.$$
 (1)

One proposed solution to overcome the limiting RC time constant is the traveling-wave diode (TWD).¹⁰ The antenna excites a surface plasmon wave that travels down an elongated MIM diode forming a transmission line. As the wave propagates, it is rectified by the MIM diode. Since the antenna is now loaded by a rectifying transmission line, the impedance seen by the antenna is the input impedance of the line, rather than the lumped-element impedance of the MIM structure. Just as with a transmission line, the capacitance of a TWD is distributed and does not limit the frequency response. The frequency response is limited by other factors, dominantly the increasing resistance of the metals with frequency, which gives rise to a plasmonic decay. Finite element modeling has examined the effects of the geometry on the TWD rectenna¹¹⁻¹⁴ and indicated that the TWD should improve coupling between the antenna and diode over the coupling with a lumped-element diode. The TWD optical rectenna has been demonstrated experimentally in a configuration where the antenna is



FIG. 1. Traveling-wave diode (TWD) vs a lumped-element rectenna: (a) a notional example of a lumped-element rectenna, (b) a notional example of a TWD rectenna, and (c) an antisymmetric coupled surface plasmon mode.

coupled to a silicon wave-guide to detect 1.6 μ m using a symmetric diode with an external voltage bias by Hobbs *et al.*¹⁵ We expand on the first demonstration of a self-powered TWD rectenna responding to free-space infrared illumination.¹⁶

II. TRAVELING-WAVE STRUCTURE

A TWD differs from a lumped-element rectenna primarily in the method it is fed from the antenna. As Fig. 1(a) shows, in a lumped-element configuration, the diode is located at the feed point of the antenna, where it receives a voltage signal uniformly across the diode. Each antenna leaf is connected at opposite ends of the diode and the plasmonic waves from each leaf propagate toward each other. A TWD, on the other hand, as shown in Fig. 1(b), requires a transition at the feed point of the antenna so that the signals from each leaf of the antenna turn perpendicular to the antenna axis and propagate in the same direction. This transition aligns the propagation direction of the two signals and excites a surface plasmon mode at the MIM interface. Finally, Fig. 1(c) shows the antisymmetric mode supported by the TWD MIM structure. The electric field confinement in the insulator is perpendicular to the MIM interface. This field drives the electron tunneling. When the MIM structure is designed to have an asymmetric tunneling characteristic, the tunneling results in rectification.

III. FABRICATION AND DC TESTING

The TWD rectenna reported in this work was fabricated with the germanium shadow mask (GSM) process summarized in Fig. 2, similar to the method used by Hobbs *et al.*^{15,17} and our previous work.¹⁶

We start with a silicon wafer with a 300 nm layer of thermally grown SiO₂. We spin polymethyl methacrylate (PMMA) in a 4% anisole solution onto the wafer to a thickness of 260 nm and coat the surface with 60 nm of evaporated germanium. We pattern the surface with an ASML 5500 248 nm DUV stepper with the top view image in the inset of Fig. 2. We etch the pattern into the germanium with a CF₄ etch and remove the underlayer of PMMA with a O₂ plasma clean. The O₂ plasma is run at a relatively high pressure (\approx 700 mT) to ensure the PMMA removal undercuts the Ge by at least 0.5 μ m. Looking at the cross section indicated in the inset of Fig. 2, the resulting structure has a suspended Ge bridge.

The shadow mask can be used to build single or double insulator MIM diodes. We use double insulator MIM diodes



FIG. 2. Germanium shadow mask fabrication process. The seven distinct regions, from left to right (1: Ni only, 2: Ni/oxides/Cr/Au, 3: Cr/Au only, 4: TWD junction Ni/oxides/ Cr/Au, 5: Ni only, 6: Ni/oxides/Cr/Au, and 7: Cr/Au only).

because of the higher nonlinearity and asymmetry.¹⁸ Specifically, we fabricate a Ni-NiO-Nb₂O₅-Cr/Au structure. To form a step diode,¹⁸ we need a low dielectric insulator to form a low barrier with the corresponding metal. The Ni-NiO interface gives a low barrier, and the NiO has a low relative permittivity compared to Nb₂O₅.¹⁹ Cr forms a reliable junction with Nb₂O₅ without an excessively high barrier but has poor plasmonic properties. Therefore, the Cr is deposited to a thickness of only 3 nm and is capped in a thicker Au layer that greatly improves the plasmonic propagation along the TWD without degrading the *I*(*V*) characteristics.

To build this double insulator MIM diode with the germanium shadow mask, first, 45 nm of Ni is evaporated at a 43° from the right. Then, a nickel oxide is grown to a thickness of ~ 3 nm in an O₂ plasma at 30 W and 50 mT. Nb₂O₅ is DC reactively sputter deposited from a Nb target in an O₂/Ar plasma at 60 W and 3 mT to a thickness of ~ 2 nm. Next, a 3 nm layer of Cr and a 30 nm layer of Au are evaporated at normal incidence. Finally, the PMMA is dissolved in an acetone bath to lift off the Ge and the excess metal (Ni, Cr, and Au) that deposited on the Ge.

We imaged the resulting structure with a scanning electron microscope (SEM) to check that the process worked as intended. Figure 3 shows an SEM image of the completed device. We can see the offset in the two metal depositions that slightly distort the pattern from what is etched into the Ge. The cross section in Fig. 2 yields seven regions with varying combinations of Ni and Cr/Au (only Ni, only Cr/Au, and Ni/Cr/Au). These seven distinct regions are visible (and labeled) in the SEM, shown in the illustrated cross section in Fig. 2, and the TEM in Fig. 4. It is worth noting that there are two other MIM junction. Based on the SEM images, the area of these junctions is almost 20 times larger area than that of the TWD and thus have a resistance that is commensurately lower. Since none of the junctions are highly nonlinear, considering them



FIG. 3. SEM of TWD after liftoff. The seven regions from the GSM process are labeled 1–7 from left to right.



FIG. 4. TEM of a representative TWD after liftoff. The overlap is 115 nm and the length is 1350 nm. (a) A magnified cross section of the MIM tunnel junction, (b) expanded view of entire TWD structure, and (c) illustrated expanded TWD cross section for comparison.

as area-dependent resistances is approximately correct. Because of the much lower resistance of the additional junctions, we may ignore their effects.

From the SEM, we can measure critical dimensions such as TWD length and overlap which are necessary to estimate expected device performance. This particular device, for which we show an infrared response in Sec. IV, is 1350 nm long and has a 115 nm overlap. A transmission electron micrograph (TEM) of a similar device shown in Fig. 4 confirms that the shadow mask process yields the expected cross-sectional geometry.

The SEM image is of the specific device for which we report an optical measurement, while the TEM was taken from a similar device fabricated with an identical procedure due to the destructive nature of the TEM sample preparation. The TEM reveals that the illustrated cross section is quite representative of the actual structure. Using 300 nm resolution lithography, we achieved a ~ 100 nm overlap geometry. This comes at the cost of distorted geometries for the rest of the features as shown by the SEM in Fig. 3. This distortion limits our ability to engineer the antenna or transition region.

After the fabrication is complete, we measure the diode DC I(V) characteristics with a four-point probe measurement. While the DC I(V) characteristic is probably not the same as the high-frequency I(V) characteristic,²⁰ it is impossible to measure the I(V) at terahertz frequency. Measuring the DC characteristic provides an indication of the film and junction quality. The I(V) data are fit with the exponential fit equation;²¹ additional details can be found in Subsection 1 of the Appendix.

The resulting diode I(V) characteristics are summarized in Fig. 5. We can see from Fig. 5(a) that the exponential fit used fits the I(V) data well. The asymmetry curve in Fig. 5(c) shows that this diode is asymmetric, and we can expect this diode to rectify without applying a bias voltage.

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FIG. 5. MIM diode I(V) characteristics. (a) Measured diode I(V) raw data (red circles) and exponential fit (blue line), (b) fit responsivity, (c) fit asymmetry (blue line) and interpolated data asymmetry (red dots), and (d) exponential fit diode differential resistance.

From Fig. 5(d), this diode has a zero-bias resistance of 380Ω , and from Fig. 5(b), the diode has a zero-bias responsivity of 0.46 A/W. There is a tradeoff between the desirable characteristics of low resistance and high responsivity.²² This is one of the lowest resistance/highest responsivity diodes reported to date.

IV. OPTICAL MEASUREMENT

To test the high-frequency response of the TWD rectenna, we illuminated it with $10.6 \,\mu$ m linearly polarized radiation from a CO₂ laser (SYNRAD 48-1SWJ). The laser is pulse-width modulated (PWM) with a function generator (Agilent 33220A) at 20.0 kHz with a duty cycle of 20%. First, we characterized the laser beam profile with a razor blade measurement and a Scientech Astral AI310 calorimeter. We find the beam to be Gaussian with a full width at half maximum of 4.9 mm and a maximum pulse intensity of 1 W/mm². The beam is large enough that we can confidently position our device at the center of the beam where it will receive the maximum intensity from the incident radiation. The beam passes through a shutter and a half-wave plate prior to exposure on the TWD, as shown in Fig. 6. The shutter allows us to measure the noise level from the lock-in under dark conditions.

The half-wave plate rotates the polarization of the incident beam. In the starting position of the half-wave plate, $\Theta = 0^{\circ}$, the laser polarization is aligned with the antenna axis. The half-wave plate rotates the beam in the counterclockwise direction. The opencircuit voltage, V_{oc} is measured using the lock-in amplifier (SR830) versus the polarization of the incident radiation relative to the



antenna axis. The reference for the lock-in amplifier is generated by a mechanical chopper at 1694 Hz. The magnitude of the voltage measured using the lock-in amplifier is the RMS voltage of the sine wave at the reference frequency, but the signal from the rectenna is a square wave at the frequency of the mechanical chopper. Therefore, there is a correction factor of $\pi/\sqrt{2}$. There is a second correction factor, (duty cycle)⁻¹, due to the unconventional setup which modulates a pulsed laser with a mechanical chopper. Since we take the input illumination to be the peak intensity of the pulse, we need to correct the voltage read by the lock-in by a factor of 1/(duty cycle).

As expected, the measured open-circuit voltage signal, shown in Fig. 7, peaks at 0° and 180°, when the polarization is aligned with the antenna axis and is minimized when the incident E-field is off-axis. This minimum approaches the noise level (average \sim 39 nV) shown by the dashed blue line.

It is notable that the TWD minimum, off-axis, response does reach the noise level. We have found that the TWD can absorb IR radiation directly when the polarization is aligned along the TWD length (off-axis from the antenna). This direct absorption leads to heating of the MIM and a Seebeck voltage. Additional details describing this effect can be found in Subsection 2 of the Appendix. Because of this off-antenna-axis absorption mechanism, we fit the data with the following equation:

$$V_{oc}(\theta) = A_{\parallel} \cos^2(\theta + \phi) + A_{\perp} \sin^2(\theta).$$
⁽²⁾

When the polarization is aligned with the antenna axis, A_{\parallel} is the magnitude of the voltage signal and A_{\perp} is the magnitude of the voltage signal when the incident polarization is off-axis. The additional variable, ϕ , accounts for misalignment of the antenna axis with the incident polarization, and potential absorptions change due to unintentional asymmetry in the antenna leaves that can be seen in the SEM in Fig. 3. When the optical data are fit with (2), we find the following fit coefficients, with the 95% confidence



FIG. 7. TWD open-circuit voltage optical response versus polarization angle relative to the antenna axis. The V_{oc} data are shown as blue dots. The \cos^2 fit is shown in solid red. The 95% confidence interval (CI) is shown by the dashed red line. The noise level is shown by the dashed blue line.

interval listed in parentheses:

$$A_{\parallel} = 1200 \text{ nV} (1190, 1260), \quad A_{\perp} = 95 \text{ nV} (63, 128),$$

 $\phi = -4.3^{\circ} (-5.5, -3.0), \qquad R^2 = 0.9918.$

The relatively low value of A_{\perp} , close to the measured noise level, indicates that there is almost no signal from heating of the TWD due to direct absorption at off-axis polarization illumination. The coefficient accounting for misalignment, ϕ , is relatively small. The rectenna open-circuit voltage response, V_{oc} , is represented by A_{\parallel} . Short-circuit current, I_{sc} , can be estimated from V_{oc} using R_d , the diode zero-bias differential resistance, and Ohm's law because the I(V) curve is close to linear at low voltages. Thus, I_{sc} is 3.2 nA. Using I_{sc} or V_{oc} , we can calculate the system responsivity as follows:

$$\beta_{sys} = \frac{I_{sc}}{P_{in}} = \frac{V_{oc}}{R_d P_{in}}.$$
(3)

Whereas the diode responsivity in Fig. 5 is the DC output current for a given electrical power supplied to the diode, the system responsivity is the DC output current for a given optical illumination power incident on the rectenna. The illumination power, P_{in} , is calculated as the product of the illumination intensity and absorption area (estimated in Ref. 14). For the measurement in this work, the absorption area is estimated to be $24 \,\mu\text{m}^2$. Given that the illumination intensity is 1 W/mm², P_{in} is $24 \,\mu\text{W}$. From (3), β_{sys} is $130 \,\mu\text{A/W}$. We can also calculate detectivity, D*, a common detector performance metric. Detectivity has units of Jones (cm $\sqrt{\text{Hz}} \,\text{W}^{-1}$) and is calculated as follows:

$$D^* = \beta_{sys} \sqrt{A_{Abs}} \sqrt{\frac{R_d}{4kT}},$$
 (4)

where *k* is Boltzmann's constant and *T* is the room temperature. Using I_{sc} of 3.2 nA, D* is 1.0×10^4 Jones.

V. DISCUSSION AND CONCLUSION

A. Performance analysis

We compare the measured TWD response to the performance predicted by simulation and the calculation of the estimated response of an equivalent lumped-element diode, i.e., an MIM with identical I(V) characteristics and diode size, but coupled to the antenna in a lumped-element configuration. We developed the TWD model¹⁴ and incorporate the dimensions and I(V) characteristics of our fabricated device. The simulation predicts $I_{sc} = 6.0 \text{ nA}$ or a $D^* = 1.8 \times 10^4$ Jones. Using the lumped-element rectenna performance calculation from the same work, we find the estimated lumped-element detectivity to be 7.0 \times 10^2 Jones and $I_{sc} = 0.23$ nA. This is lower than our measured TWD value by a factor of ~14. A comparison of the measured TWD, simulated TWD, and equivalent lumped-element are summarized in Table I. The simulation estimated a TWD performance that is roughly 1.8 times higher than our experimental results. This discrepancy between simulation and experiment can likely be explained as arising from several possible sources. First, the simulation uses a simplified geometry compared with the full structure that results from the GSM fabrication process. Modeling a more accurate representation of the GSM TWD requires a substantial increase in computational power. Second, our model ignores the granularity of the metals and surface roughness, which in our experimental device likely reduces the plasmon decay length. Third, the simulation relies on the DC I(V) characteristic to predict high-frequency performance, but the high-frequency I(V) may be different.²⁰ Finally, the additional MIM junctions in each antenna leaf that result from the GSM fabrication method could lead to actual antenna performance that is lower than what is estimated by the simulation.

The combination of a good match (within a factor of 2) to simulation and a substantially higher measured response compared to the lumped-element estimation indicates that we have demonstrated a genuine traveling-wave response. The estimated lumped-element coupling efficiency is only 0.02%, while from the TWD simulation, we can estimate the coupling efficiency between the TWD and the antenna to be ~35%. This is an improvement of a factor of ~1700. The distributed nature of the TWD MIM circumvents the RC

 TABLE I. Summary of measured TWD, equivalent lumped-element rectenna, and simulated TWD rectenna.

	Measured TWD	Estimated lumped-element	Simulated TWD
V_{oc} (nV)	1200	87	2300
I_{sc} (nA) β_{cwc} (μ A/W)	3.2 130	0.23 9.5	6.0 250
D* (Jones)	$1.0 imes 10^4$	7.0×10^2	$1.8 imes 10^4$
Coupling efficiency Plasmonic loss	N/A ^a N/A ^a	0.02% 0%	35% ~99%

^aIndicates not experimentally accessible.

limitation of the MIM junction and allows for this improvement. Unfortunately, despite the improvement in coupling by a factor of \sim 1700, the TWD improvement over the lumped-element is limited to \sim 14 because there is an additional loss mechanism, the propagation of the surface plasmon along the MIM interface. The thin insulator required to support electron tunneling leads to a very high field confinement and lossy plasmonic propagation. This plasmonic loss consumes \sim 99% of the plasmonic power. (Please see the supplementary material for additional details on values calculated in Table I.) In a lumped-element rectenna, once the AC power enters the diode, all of it is available to be rectified. The TWD on the other hand requires the plasmonic power to propagate along the lossy MIM interface. So, while the coupling efficiency is greatly improved, the overall improvement is limited by this additional loss mechanism.

B. Future work

From our simulation work,¹⁴ we know our antenna has poor directivity and only absorbs ~10% of the incident radiation. The simplest way to improve overall performance would be to improve the absorption efficiency of the antenna by modifying the measurement configuration to accommodate backside illumination or changing the SiO₂ thickness so that it is quarter-wave matched for 10.6 μ m wavelength.²³ Additional work to further improve the MIM *I*(*V*) characteristics would improve overall performance.

The TWD rectenna has potential to be competitive with commercially available IR detectors. For example, the PVM-10.6 HgCdTe photodiode made by Boston Electronics has a responsivity of $3.2 \text{ mA/W} \pm 20\%$. This is a factor of ~ 24 higher than the system responsivity of our measured TWD rectenna. With additional development, a competitive IR detector is within reach for the proposed TWD design. The plasmonic loss inherent in the TWD design prevents its use as an effective energy harvester. However, these TWD results provide an important insight necessary for making an efficient energy harvesting IR rectenna; primarily, we have demonstrated that we can engineer around the RC time-constant limitation of MIM diodes and achieve high coupling efficiencies between the antenna and diode in the infrared. This suggests that it may be possible to design a low-loss structure to circumvent the MIM capacitance and achieve useful operating efficiencies.

SUPPLEMENTARY MATERIAL

See the supplementary material for a discussion on the estimated antenna coupling efficiency and detailed fabrication figures.

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APPENDIX: *I(V)* FITTING AND THERMAL RESPONSE 1. *I(V)* fitting

$$I(V) = I_0(e^{bV_D(\alpha, R_s, V)} - e^{dV_D(\alpha, R_s, V)}),$$
(A1)

$$V_D(\alpha, R_s, V) = V - I(V)(R_s + \alpha V^2).$$
(A2)

The resulting fit parameters are as follows: $b = 11.00 \text{ V}^{-1}$, $d = 9.99 \text{ V}^{-1}$, $I_0 = 1.31 \times 10^{-4} \text{ A}$, $\alpha = 386 \frac{\Omega}{V^2}$, and $R_s = 16 \Omega$.

2. Thermal response

To explain the off-axis polarization response sometimes observed from illuminated TWD rectenna, we built a metal-only TWD structure. We fabricated a 2μ m long TWD as described in Sec. III, with the exception that the diode oxide processing steps were excluded. Without the oxides, the device has a very low resistance and linear I(V) characteristic, ensuring this device cannot have a rectification response,²⁴ nor can it be bolometric because there is no external bias. The only possible mechanism for a response from this metal-only TWD structure is a Seebeck voltage. Figure 8 shows the optical response of this device to the PWM laser with a 9% duty cycle and modulated by the mechanical chopper at 1.70 kHz.

Since there is experimentally almost no \cos^2 response, we adjusted the fit equation (2) so that the polarization shift term, ϕ , was part of the \sin^2 term rather than the \cos^2 term, as ϕ cannot have any meaningful effect if the amplitude coefficient is very



FIG. 8. Metal-metal (Ni-Cr/Au) junction open-circuit voltage illumination response due to the Seebeck effect and direct heating of the traveling-wave region.

small. Below, we list the fit coefficients with the 95% confidence intervals in parentheses:

$$A_{\parallel} = 85 \text{ nV}$$
 (69, 102), $A_{\perp} = 197 \text{ nV}$ (179, 215),
 $\phi = -11.5^{\circ}$ (-21.4, -1.8), $R^2 = 0.8312$.

As the figure shows, there is no on-axis (antenna-axis) response, only an off-axis, as A_{\parallel} is near the noise level of ~66.7 nV. Direct heating due to off-axis absorption in the TWD region of the rectenna can result in a thermal signal. Seebeck coefficients for Ni, Cr, and Au are -15μ V/K, 22 μ V/K, and 6.5 μ V/K, respectively.²⁵

Therefore, it would only take a very small temperature difference, 0.03 K, to account for the voltages measured. If absorption in the TWD region can give rise to a Seebeck voltage from direct heating, radiation absorbed in the antenna could theoretically result in heating and a Seebeck response as well. However, given that we do not see an on-axis response, this suggests that any heating in the antenna absorption is not strong enough to result in a thermal response, which supports the conclusion that the \cos^2 response from the MIM TWD rectenna in Fig. 7 is indeed optical rectification. The angular shift, ϕ , is within the expected range, and the coefficient of determination, R^2 , is moderately close to 1, indicating this fit accurately represents the data. This thermal signal is very small in the TWD rectenna reported in Fig. 7 because the TWD length is much shorter than the device results shown in Fig. 8.

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