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Tunable Surface Plasmon Polaritons with Monolithic Schottky Diodes

Yifei Zhang[†], Haotian Ling[†], Pingjian Chen[†], Pengfei Qian[†], Yanpeng Shi[†], Yiming Wang[†], Huayu Feng[†], Qian Xin[†], Qingpu Wang^{†*}, Shouyuan Shi[‡], Xiaomin Pan[§], Xinqing Sheng[§], and Aimin Song^{†,‡,*}

[†]Center of Nanoelectronics and School of Microelectronics, Shandong University, Jinan, China

[‡]Department of Electrical and Computer Engineering, University of Delaware, Newark, DE, U.S.A.

[§]School of Information and Electronics, Beijing Institute of Technology, Beijing, China

[‡]School of Electrical and Electronic Engineering, University of Manchester, Manchester, United Kingdom

Supporting Information Placeholder

ABSTRACT: Surface plasmon polaritons (SPPs) provide sub-wavelength electric field confinement ranging from microwave to the visible. Several approaches have been explored to manipulate SPPs with a typical modulation capability of only a few percent. Here, active control of SPPs using monolithically fabricated Schottky diodes has been first designed and realized, achieving a continuous and significant modulation of transmission, reflection, and absorption. The SPPs propagating on a metal line are attenuated by using split ring resonators (SRRs) with an In-Ga-Zn-O Schottky diode bridging each SRR split gap. The resistance of the diodes can be tuned over a range of a few orders of magnitude with bias voltage, which continuously transforms each SRR to a metallic quasi-loop with subdued resonance. A remarkable modulation of 40% and 19% was demonstrated for the transmission and absorption, respectively, which to the best of our knowledge has not been achieved before.

INTRODUCTION

Surface plasmon polaritons (SPPs) are propagating surface waves with highly confined electric field at the interface between two different materials with opposite permittivities.¹⁻⁵ With the advantages of non-diffraction limit and strong electric field enhancement, SPPs have found many applications from microwave to optical frequencies, such as super-resolution imaging, miniaturized sensors, photovoltaics, miniaturized integrated circuits etc.⁵⁻¹³ SPPs were originally found at metal-dielectric interface in visible and near-infrared spectra due to the plasmonic properties of noble metal and the corresponding negative permittivity.¹⁻³ However, these conventional optical SPPs cannot operate at far-infrared, terahertz (THz), and microwave frequencies where metals are perfect electric conductors.¹⁴⁻²⁶ As such, metal sheets with periodic holes or grooves (typically referred to as spoof SPPs), semimetals (such as graphene), semiconductors, and topological insulators have been utilized for SPPs at infrared frequencies and below.²⁴⁻²⁹ Recently, planar and even conformal 2-D metallic line structures have also been proposed to transmit spoof SPPs at THz and microwave frequencies.¹⁴⁻²³ Their advantages include not only conservation of the intrinsic properties of optical SPPs, e.g., non-diffraction limit, but also low propagation losses, high immunity to electromagnetic couplings, and simple integration with transmission lines, such as co-planar waveguides (CPWs).

Apart from passive SPPs, active SPP devices with electrically tunable properties enable applications in real-time controllable sub-wavelength circuits, such as switches, attenuators, phase and frequency shifters etc.^{12,13} At optical frequencies liquid plasmonic materials, ferroelectric materials, semiconductors, and P-N diodes have been studied to actively manipulate SPPs.³⁰⁻³⁶ However, their modulation depth is typically less than 20%. To achieve tunable SPPs at microwave frequencies, commercially purchased chips, such as varactor diodes, have been soldered on SPP devices.²¹⁻²³ However, these soldered chips were not monolithically fabricated with the SPP structures. Their device size and integration tolerance have so far limited their operating frequency to below 15 GHz. In addition, graphene has recently been investigated to integrate with SPP structures for both tunability and monolithic fabrication over a wider frequency range.³⁷⁻⁴⁰ However, to the best of our knowledge, the modulation depth of such graphene based active SPP devices only reaches a few percent in experiments.⁴¹

Here we propose to monolithically fabricate Schottky diodes with a novel subwavelength SPP structure, which enables a significant modulation of transmission, reflection, and absorption for SPPs at millimeter wave frequencies. The proposed device consists of single split-ring resonators (SRRs) on a SPP waveguide and In-Ga-Zn-O (IGZO) Schottky diodes fabricated to bridge the SRR split gaps. The diode can actively tune the conductivity within the split gap so that the resonance magnitude of SRRs and the corresponding attenuation of SPPs are modulated. The characterized continuous modulation depth of transmission and absorption is 40% and 19% at 49 GHz, respectively, which is, to the best of our knowledge, the record for SPPs. Based on the averaged conductivity derived from the current-voltage measurement of the IGZO Schottky diode, finite element method (FEM) simulation reveals an ideal modulation range of 67% for SPP transmission.

NOVEL SPP DEVICE WITH SRRS

As illustrated in Figure 1a, a novel SPP structure, consisting of two 50-Ω CPWs (I), two CPW-to-SPP waveguide transitions (II), and one SPP waveguide with SRRs (III) is designed on a silicon substrate with a thickness of 200 μm and a 100-nm SiO₂ layer. Typically, rectangular slots or complementary corrugations are used for spoof SPPs to achieve a spectral cut-off response.¹⁶⁻²⁰ Here, single-loop SRRs are proposed to get the cut-off response and band-stop respo-

Figure 1. CPW fed SPPs with SRRs: (a) Driven Mode 3-D model; (b) Eigen Mode 3-D models of SPP waveguides with square corrugations, SRRs, and loops in periodic boundary ($L_1 = 9$ mm, $W_1 = 3$ mm, $R = 7$ mm, $P = 0.71$ mm, $W_s = 80$ μ m, $W_g = 60$ μ m, $W_m = 44$ μ m, $L_2 = 130$ μ m, $L_m = 162$ μ m, $W_2 = 20$ μ m, $G = 2.4$ μ m, $L_3 = 56$ μ m, $T_1 = 43$ μ m, $T_2 = 86$ μ m, and $T_3 = 130$ μ m); (c) Simulated norm of electrical fields at the metal-dielectric interface at the resonant (49 GHz) and non-resonant (60 GHz) frequencies.

Figure 2. Simulated and measured data and measurement system set-up: (a) Dispersion diagram of the SPP waveguides with corrugations, SRRs, and loops; (b) System set-up with PNA and G-S-G probes; (c) S21 and (d) S11 of the proposed passive device.

nse simultaneously, the latter of which is induced by the resonance of SRRs. The CPW-to-SPP waveguide transition is achieved by flaring out CPW ground electrodes and distributing rectangular corrugations with linearly increased length, whose detailed design can be found in References 17 and 22. Then, SRRs are designed to replace the corrugations without shifting the cut-off frequencies. The resonant frequency of SRRs can be tuned by varying the length (L_2) and width (G) of the gap.

To clarify the SPP cut-off properties, unit cells of SPP waveguides with rectangular corrugations, SRRs, and loops were simulated with periodic boundary using Ansys High Frequency Structural Simulator

(HFSS) Eigen Mode solver. Figure 1b shows their models with a period of $P = 0.71$ mm, and Figure 2a illustrates their dispersion diagrams. It can be seen that the dispersion curves of the SPP waveguides with corrugations and loops show a similar phenomenon as the optical SPPs and have little discrepancy with each other.^{1,24} The SPP waveguide with SRRs has an additional stop band compared to its counterparts with loops and corrugations. To calculate S-parameters and electric fields, 3-D models of the proposed devices were built in HFSS Driven Mode solver and simulated in a radiation boundary with two wave ports as the input and output for the CPWs. The optimized dimensions of a SPP device with its stop band centered at 49 GHz are listed in the caption of Figure 1. The proposed

Figure 3. (a) Top view of the fabricated active SPP device with IGZO Schottky diodes; (b) Fabrication steps; (c) Diagram of the substrate and depletion region near the SRR split gap at zero bias; (d) Equivalent circuit model of the reconfigured SRR.

device addresses a miniaturized size of $0.052\lambda_0 \times 0.278\lambda_0$ at its resonant frequency. As illustrated in Figure 1c, SPPs attenuate significantly at the band-stop frequencies, e.g., 49 GHz, due to the strong resonance of the SRRs, and propagate with little attenuation at the non-resonant frequencies, e.g., 60 GHz.

Agilent programmable network analyzer (PNA) N5247 was used to characterize the proposed passive and active devices, and the system set-up is depicted in Figure 2b. 50- Ω ground-signal-ground (G-S-G) probes integrated with PNA were first calibrated with CS-5 on-wafer calibration chip, and then launched on the two CPWs for signal input and output. The measured S-parameters of the passive device are illustrated in Figure 2c and 2d, showing good agreement with the simulated ones. The device has a stop band centered at 49 GHz with a Q-factor of 93, and its maximum bandstop attenuation is -31 dB. The propagation attenuation is less than 2.2 dB in the pass band, which can be mainly attributed to the insertion loss of the CPW-to-SPP waveguide transitions (Supporting information, Figure S1).

MODULATION WITH SCHOTTKY DIODES

Inspired by tunable metamaterials with gallium arsenide (GaAs) Schottky diodes,^{42,43} for the first time Schottky diodes are proposed to actively manipulate SPPs here, as shown in Figure 3a. The diodes are fabricated using IGZO oxide semiconductor to bridge the split gaps of SRRs. Compared to GaAs, IGZO can be sputtered onto various substrates, including the flexible ones.⁴⁴⁻⁴⁸ The Schottky and ohmic contacts of the diode are the SRRs and CPW grounds, respectively. To minimize the impact to SPP propagation, the ohmic contact is designed around 1.2 mm away from the SRRs (Supporting information, Figure S1c). The corresponding fabrication steps are illustrated in Figure 3b. First, the signal electrode (Schottky contact) was fabricated by conventional photolithography and electron-beam deposition of 10 nm titanium, 300 nm gold, and 50 nm palladium. Next, a 750-nm IGZO film was grown by using sputtering at room temperature. Finally, the ground electrode (ohmic contact) was deposited by using 10-nm titanium and 300-nm gold. In this case, a Schottky junction is formed between the IGZO film and the signal electrode, as shown in Figure 3c, which could be demonstrated by the DC current-voltage measurement (Supporting information, Figure S2a).

The equivalent circuit model of the proposed approach is a *RLC* resonant circuit depicted in Figure 3d, where L is the inductance of the ring loop, C is the capacitance of the split gap, and R_g represents the variable attenuation due to the substrate free carrier absorption within the split gap. At the resonant frequencies, e.g., 49 GHz, SPPs are attenuated by the SRR resonance significantly, as illustrated in Figure 1c. At zero bias, the IGZO film in the split gap is depleted so that the SRRs resonate normally and thus shows a perfect band-stop response. This initial state corresponds to the blue curve in Figure 2c. As the forward bias increases, the free carriers with increasing density short out the capacitor gradually, as illustrated in Figure 3d. Thus, the SRR resonance becomes subdued, and the SRR with Schottky diode works more and more like the metallic loop illustrated in Figure 1b, which leads to smaller attenuation for SPP propagation. Ideally, the ultimate state is the red curve in Figure 2c, and the active modulation curve should locate between the blue and red curves.

The measured S-parameters of the active device are illustrated in Figure 4a and 4b, showing a large modulation of both transmission and reflection. The transmission was modulated from -31 to -6.9 dB at 49 GHz with a varying forward bias, which corresponds to a modulation depth of as high as 40% in Figure 5a. The maximum forward bias applied is 46 V, which is limited by the protect voltage of the PNA bias-Tee. Note that little spectral shifting of the resonant frequency was observed in our measurement. This phenomenon can be explained by the quasi-constant capacitance of the Schottky diode with a forward bias (Supporting information, Figure S2c), which remains fairly stable as a function of frequency.⁴⁴ To further reveal the tunability of the proposed device, the absorption and differential transmission defined as $\Delta T/T_0$ are plotted in Figure 4c and 4d, respectively (ΔT is the transmission discrepancy, and T_0 is the transmission at zero bias). A dramatic modulation range of 19% is demonstrated for the SPP absorption. With respect to the zero-bias case, the absorption first increases at a bias of 5 V, then decreases due to the increasing conductivity within the SRR split gap as the bias further enlarges. As can be seen from Figure 4d, the differential transmission increases continuously as the applied voltage enlarges. At a bias of 46 V, $\Delta T/T_0$ is as high as 257, which to the best of our knowledge is the highest for the active SPP devices.

Figure 4. Modulation performance of the active SPP device at different forward bias: frequency-dependent (a) Transmission, (b) Reflection and (c) Absorption of the device at different bias, (d) Differential transmission of the device with respect to the transmission at zero bias.

Figure 5. (a) Measured and (b) Simulated normalized transmission of the active SPP device.

To reveal the ideal modulation range, averaged conductivity of the IGZO film was extracted from the DC current-voltage measurement of the Schottky diode (Supporting information, Figure S2b), which changes from 7.9×10^{-6} to 0.23 S/m with bias sweeping. Thus, a sheet with different conductivities was designed for IGZO to bridge the

SRR gap in full-wave HFSS simulation. Figure 5 depicts the normalized transmission curves extracted from the measured and simulated S-parameters (Supporting information, Figure S3), whose discrepancy can be mainly attributed to the structure difference between the simulation model and fabricated device. Although surface roughness, fabrication tolerance, and spatial non-uniformity of conductivity in IGZO film are not considered in the simulation, the simulated and measured data still show reasonable agreement. As the orange curve depicted in Figure 5b, the device has little bandstop attenuation at 49 GHz with a conductivity of 0.016 S/m, which can be easily obtained with a higher forward DC bias. In this case, the ideal modulation range of the transmission and absorption is 67% and 32%, respectively, and the corresponding differential transmission is as high as 573. Due to the large distance between the ohmic and Schottky contacts, the applied bias here is higher than several reported works.^{35, 36} However, the applied bias is dominantly dropped over the long IGZO channel and the power dissipation is distributed over a wide range. Several devices have been tested successfully without any breakdown in the aforementioned voltage range.

CONCLUSION

Monolithic oxide-semiconductor based Schottky diodes have been demonstrated to successfully manipulate SPPs with subwavelength size, achieving a remarkable modulation depth of 19% and 40% for the absorption and transmission at millimeter wave frequencies, respectively. This approach is highly practical because oxide semiconductors can be deposited on large-area and/or flexible substrates at a low cost using sputtering method. The demonstrated tunable SPP devices may be scaled to other microwave and THz frequencies and/or integrated further with other components for more functional monolithic integrated circuits.

ASSOCIATED CONTENT

Supporting Information

(1) HFSS model of CPW-to-spoof SSP transitions and the extracted insertion loss; (2) DC response of the proposed Schottky diode; (3) simulated modulation of the active spoof SPP device with an IGZO film of different conductivity. (PDF)

Fabrication

The substrate was sequentially cleaned in an ultrasonic bath with decon, de-ionized water, acetone, and ethanol, and then dried by N₂. The signal electrodes of CPWs and SPP waveguide (Ti 10 nm/Au 300 nm/Pd 50 nm) were defined using the laser direct writing (LDW), deposited with electron-beam evaporation, and patterned with lift-off process. The Pd layer was treated with oxygen plasma (PDC-21G, 30min) for oxidation to ensure good oxygen stoichiometry of the contact interface before IGZO deposition. Then, a 750-nm-thick amorphous IGZO layer was deposited with a target of In:Ga:Zn=1:1:1 in atomic ratio (Lesker Co.) and a mixed gas of 97.5% argon and 2.5% oxygen by using radio-frequency (RF) magnetron sputtering at room temperature. The RF sputtering power was 70 W and the working pressure was 3.63 mTorr. Finally, the ground electrodes of CPWs and DC bias (Ti 10 nm/Au 300 nm) were also defined by LDW, deposited with electron-beam evaporation, and patterned with lift-off as the top ohmic contact.

AUTHOR INFORMATION

Corresponding Author

Email: wangqingpu@sdu.edu.cn, songam@sdu.edu.cn

Author Contributions

Y. Zhang, Q. Wang, and A. Song contributed equally to this work.

Notes

The authors declare no competing financial interests.

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Graphic entry for the Table of Contents (TOC)

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