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14. ABSTRACT This research studied the capabilities of plasmonics at optical and near infra-red frequencies to propagate electronically modulated plasmon signals over a chain of nanoparticles and nanowires. Since the propagation lengths on wires made of nanoparticles and dielectric clad nanowires are about a few 100's of micrometers, spoof surface plasmon polariton (SSPP) structures are studied to achieve signal propagation over several millimeters which are comparable to global busses in a microprocessor chip. The research also studies the effect of near-field concentration of photon fluxes at the pn-junctions of photovoltaic cells. Mathematical models for plasmonics in conjunction with FDTD and HFSS simulation results are provided.					
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AIR FORCE OFFICE OF SCIENTIFIC RESEARCH --- FINAL REPORT

Feb 14, 2011

DTIC Data (Final Report)

10 Pages + 4 Journal Papers

Purchase Request Number:**BNP:****Proposal Number:** DRDA #: 06-4661**Research Title:** Modeling, Simulation and Design of Plasmonic Interconnects for On-Chip Signal Processing.**Type Submission:****Inst. Control Number:** FA9550-06-1-0493**Institution:** The University of Michigan**Primary Investigator:** Pinaki Mazumder**Invention Ind:****Project/Task:****Program Manager:** Dr. Gernot Pomrenke

Objectives of Research

The primary mission of this research project is to find applications of plasmonics mode information transmission in the mainstream VLSI systems through theoretical modeling and simulation tools. The project will strive to meet the following objectives:

- **Objective #1:** To develop a new Plasmonic Interconnect Simulator Tool (PIST) that will demonstrate surface plasmon (SP) pulse propagation along the MNPs array and the MNW;
- **Objective #2:** To develop general theory of energy transfer mechanism in metallic nanoparticles (MNPs) array and metallic nanowire (MNW) so that SPICE-compatible equivalent models can be designed for MNP's and nanowire;
- **Objective #3:** To develop the passive circuit elements (R, L, C, G) of MNPs array and MNW that will offer us fast system-level simulation models such as SPICE;
- **Objective #4:** To perform the circuit level simulation, SPICE for realizing plasmonic wave;
- **Objective #5:** To find on-chip applications of plasmonic waveguides and to develop integrated SPICE modeling capability of photonics and electronic signals;
- **Objective #6:** To develop an active plasmonic switch or modulator which will perform more complete signal routing and process arbitrary Boolean logic;
- **Objective #7:** To design ultrafast and highly sensitive nanophotodetector to convert optical signal to electronic signal in a very small plasmonic architecture.

Basic Science Content of Research -- Fundamental Physics of Plasmonics

- Surface Plasmons are transverse magnetic transverse field for which surface charge requires an electric field normal to the surface.

- The field in this perpendicular direction is said to be evanescent and prevents power from propagating away from the surface.
- The dispersion curve for an SP mode shows the momentum mismatch problem that must be overcome in order to couple light and SP modes together.

From these basic fundamental physics, plasmonics allows us to concentrate and channel light using sub-wavelength structures. This could lead to miniaturized photonic circuits with length scales much smaller than those currently achieved. For example, we can build up new types of nano-optics devices such as metallic nanoparticles, metallic nanoparticles array, metallic nanowire and so on.

However, the fundamental scientific challenges of nanoscale plasmonic components are that due to high attenuation of plasmonics signal, they can be only used as local elements in chip-scale applications. The issue of propagation loss along the plasmonic architecture remains to be tackled since the dimension contraction, such as transformation from two-dimensional waves to one-dimensional waves, increases damping coefficient because low-dimensional waves lead to strong momentum wave. Moreover, this significant energy attenuation in the nanoscale leads to substantial difficulties in harnessing plasmonics in on-chip nano-scale waveguide and other near field optical applications.

As another aspect, to solve the damping issues, we can decrease the operating frequency up to RF-THz frequencies. However, the plasmonic structures leads to weak localization in the RF-THz frequencies. Therefore, it is essential to find out new subwavelength localization method with small damping mechanism.

Why do we need plasmonics circuitries?

The future generation VLSI chips will seek convergence of computing and optical communications where photonic signals propagating at 100's of THz speed will stream into a VLSI chip through fiber optic cable and then the optical data will be down-converted and processed by computing circuitry operating at 10's of GHz speed.

However, the real problem is that optical waveguides used in routing optical signals are generally micron-scale wide (10-100 microns) while the electronic components will employ sub-50 nm CMOS technology causing a huge mismatch between device dimensions because the optical pulse cannot propagate along the conventional waveguide if the size dimension of waveguide is smaller than the wavelength of the signal pulse.

In order to resolve the coupling problem between optical and electronic signals, plasmonics is now being extensively pursued for fabricating nanoscale photonic components. Notably, a metal has a negative dielectric permittivity in the optical spectrum, thereby offering the light confinement in subwavelength structures and guiding light over the metallic structure. Therefore, the plasmonic devices has a potential to integrate optical components with electron devices because plasmonic components with a nanoscale have the ability to operate at optical frequencies while the physical dimensions are comparable to electronic components.

Furthermore, the promising capability of plasmonic devices to combine the electrical functionality, integration and computation can be achieved by using the photonic detection devices such as the ultrafast photodectors and nanowire field transistors.

How will Plasmonics Advance Science?

To solve the weak SPP confinement in the low frequency domain, surface topology engineering can be employed to create holes, grooves, and dimples which mimic realistic SPP behavior at the visible or ultraviolet spectrum. The resulting spoof SPP (SSPP) modes enhance the subwavelength confinement on the metal surface by generating highly localized surface bound modes in the perfect conductor.

From this property, we can demonstrate how to build efficient passive and active elements by utilizing these mimicking SSPP bound modes.

Similar to realistic surface plasmon polariton, the SSPP modes provides the interesting properties. The SSPP dispersion curves and mode profiles of the sandwiched structure provide efficient confinement methods with small damping coefficient. Hence, we can easily obtain the strong localization and small damping mechanism in the RF-THz frequency domain.

Problem Solving Approach:

First, based on electric dipole moment (EDM), we will develop the equivalent circuit elements of MNP and MNPs Plasmon wire.

Second, the passive elements of MNW are obtained by using the SP dispersion and damping curves through modified Bessel expansion, thus demonstrating the low pass transmission line modeling. With the help of equivalent circuit parameters, the circuit level simulations of MNPs array and MNW will be demonstrated by using the HSPICE simulation. We will compare those results obtained by HSPICE with FDTD based full-chip simulator tool for plasmonic interconnects (PIST). These circuit elements will enable us to simulate electronic and photonic components together in the circuit simulator framework such as SPICE.

Third, the Spoof SPP switch or modulator in the perfect conductor by designing the dispersion engineering based on dynamically changing the refractive indices of indentation of grooves will be realized by using the rigorous EM analysis. To confirm the active control switching operating at the THz frequency, we will conduct HFSS (High Frequency Structure Simulator) simulator based on the finite element method.

Finally, to realize an efficient nano-photodiode based on the surface plasmon polariton (SPP), we will employ the rigorous coupled wave analysis (RCWA) to obtain photonic maps including absorption, transmission and reflection.

Summary of accomplishments made in the past years:

Year 2: June 2007 – May 2008

Study of a chain of Metallic Nano Particles (MNP's) serving as a wire to propagate Surface Plasmon Polariton at near optical frequency: During the First Year, we realized the Objectives 1, 2 and 3. Specifically, based on the electric dipole moment (EDM) model of free oscillating electrons inside a single metallic nano-particle (MNP), a comprehensive methodology was presented for calculating the

equivalent circuit elements associated with an MNP. To find out the passive circuit elements for the MNP, the EM power flows were calculated by deriving the relaxation damping, radiation outflow, host matrix EM coupling and applied signal interaction. The law of conservation of energy was then used to compute the extended oscillatory equation motion of a spherical MNP. The resonant behavior of a single MNP was represented by a lumped resonant circuit model, where the circuit parameters (RLC) were derived from the equation of motion of the EDM and EM near-field energy outside the MNP. Finally, equivalent circuit of a linearly equi-spaced MNPs plasmon wire was modeled as a voltage controlled voltage source (VCVS) by using the nearest SP interactions (Fig. 1).

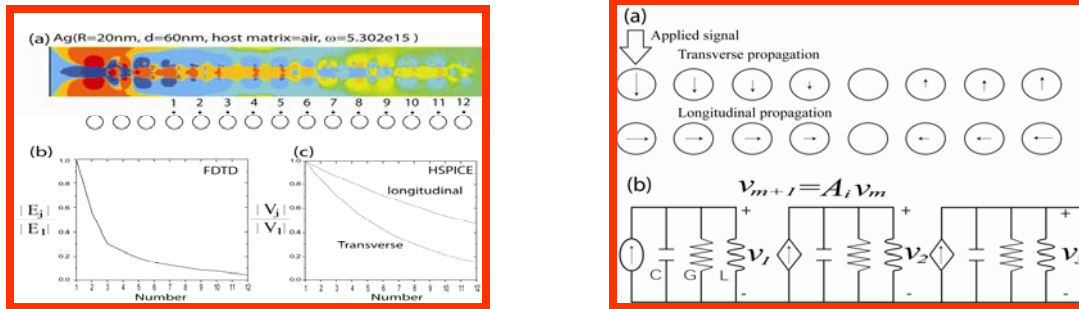


Fig. 1: To capture the main accomplishments for modeling a single nanoparticle and a chain of metallic nanoparticles (MNP's) using the RLCG model developed using the electric dipole moment (EDM) electrodynamic modeling technique. The equivalent circuit for each MNP is shown on right and the coupling between MNP's in a chain is represented in SPICE by using VCVS circuit model as shown in the right. The FDTD simulation on the top left indicates the Plasmon propagation through the linear array of MNP's. The electric field is extracted from the FDTD simulation and compared with HSPICE simulation by using the analytical model and RCG elements derived by using the electrodynamic model.

Year 2: June 2007 – May 2008

Study of a Metallic Nano Wire (MNW) serving as a wire to propagate Surface Plasmon Polariton at near optical frequency: During the Second Year, we worked towards the Objectives 3, 4 and 5. Specifically, we investigated the equivalent circuit modeling of non-radiative surface plasmon (SP) energy transport along the metallic nanowire (MNW). To find out the passive elements for MNW, the SP dispersion and damping relation through modified Bessel function electromagnetic (EM) field expansion was derived, thus demonstrating the low-pass transmission line (TL) model. Especially, the low pass TL parameters such as series impedance (Z) and shunt admittance (Y) were calculated based on the lumped element model and harmonic voltage (current) distribution. Furthermore, the equivalent circuit parameters such as resistance, inductance, capacitance and conductance were obtained by employing the finite difference (FD) discretization method such as T-cell RGLC networks. Finally, these equivalent circuit elements were verified by using the HSPICE circuit simulation and 3D scattered finite time domain method (FDTD) as shown in Fig. 2.

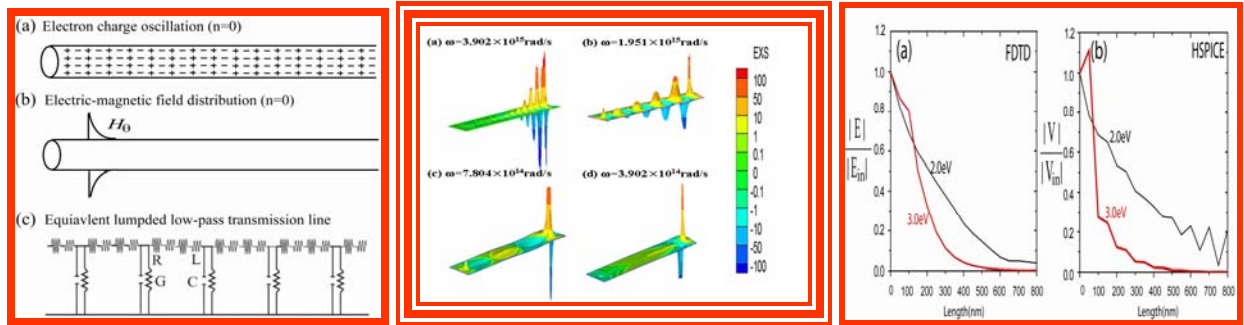


Fig. 2: Metallic Nano Wire (MNW) is embedded within dielectric medium also experiences dipole oscillation in the top left diagram along with its transmission line model due to the RLCG elements as shown in bottom left diagram. The MNW is excited at various input conditions ranging from infrared to optical frequencies, and their FDTD simulation results are shown in the middle diagram. In the right most diagram, the HSPICE simulation made using the RLCG transmission line model derived by electrodynamic model in our research is compared to the extracted E-fields from the full-wave FDTD simulation. The results tally very well to affirm that plasmonic nanowires can be simulated using circuit simulators like HSPICE to combine the electronic components and the plasmonic wires. This is an important result since previously only computation-intensive full-wave simulator like FDTD could be used to simulate Plasmon propagation through MNPs and MNW.

Year 3: June 2008 –May 2009

During the Third Year, we demonstrated the Objective 6. The feasibility of realizing a Terahertz (THz) active switch by using utilizing artificially corrugated perfect conductor meta-materials was reported by demonstrating that the strongly localized THz surface-bound Plasmon modes could be easily controlled by changing the refractive index of a periodic array of grooves. More specifically, the incorporation of EO material such as *nematic* liquid crystal (LC) into the plasmonic gap led to a highly compact and efficient THz switch that was activated by a low control signal. The optimal design of the SPP switch enabled by this novel method showed strong sub-wavelength SPP localization, relatively high extinction ratio and small damping attenuation (Fig. 3). Furthermore, the design flexibility associated with simple micron-scale architecture provided a promising method towards controlling or steering the sub-wavelength THz signal in the further SPP-based compact digital circuits (Fig. 4).

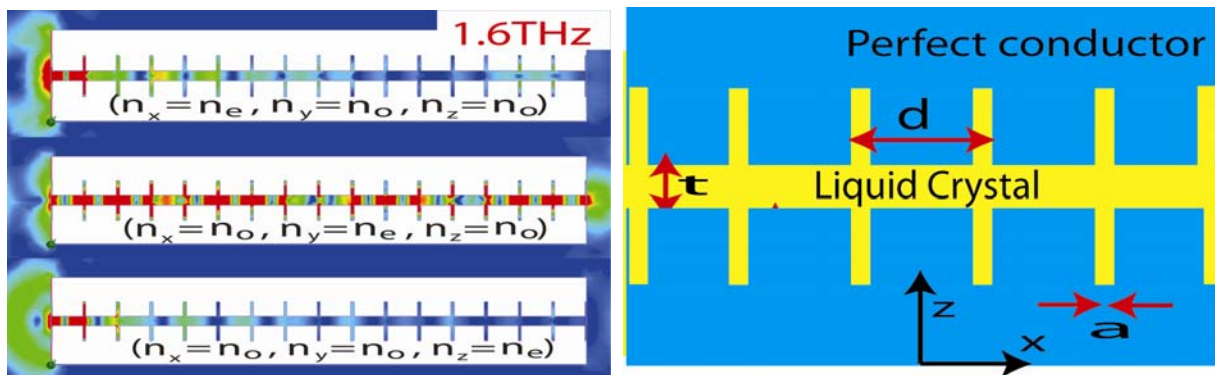


Fig. 3: Working of a SSPP switch that consists of corrugated perfect metal where nematic LCD dielectric is filled up as shown on the Right side diagram. The Left side diagram shows the snapshots when the SSPP waveguide is controlled by voltage applied to the nematic liquid crystal to turn ON and turn OFF

the Plasmon propagation through the waveguide. The control voltage changes the refractive index of the LCD which has a birefringence property where the crystals align in parallel to provide the R.I. of n_e or in perpendicular direction to provide the R.I. of n_o , as shown here. In the middle diagram, when R.I. in x and z directions is n_o , and n_e in y direction, the Plasmon propagates across the waveguide without much loss. However, if the voltage across the LCD is changed, we encounter situations like the top and bottom diagrams where the plasmon experiences nearly 12 dB attenuation and defines the OFF state of the dynamically controlled waveguide.

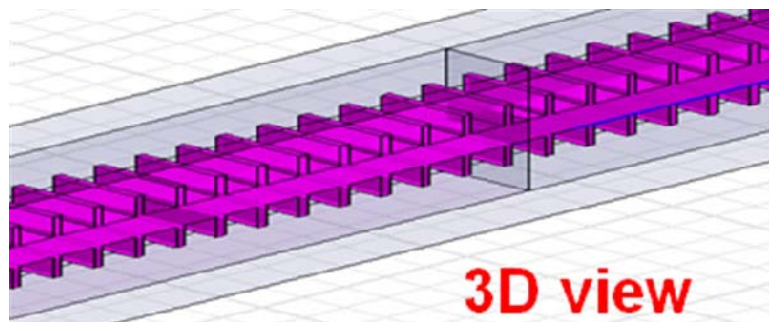


Fig. 4: The 3-D view of the SSPP waveguide is shown here to reflect that the nematic LCD dielectric engineered in the form of periodic array of grooves is embedded in perfect metal. The resulting metamaterial structure is the backbone of many inventions: (1) dynamically controlled waveguides that can be utilized to interconnect CPU block in a multi-core microprocessor, (2) Boolean switch to design ultrafast digital circuits, especially if the dimensions can be reduced to nanoscale, and (3) biosensing apparatus where biomolecules can be inserted in the cavity to create different types of spectral signatures.

Extension Year: June 2009 – August 2010

During the current year, we have been continuing to work towards the Objective 6 which has become now the cornerstone of our research. The Spoof Surface Plasmon Polariton (SSPP) mode mimics the plasmon polariton interaction to transmit signal, but in reality the electromagnetic waves resonate by bouncing back and forth in the cavities defined by the grooves inside the perfect conductor. This is similar to the oscillations inside metallic nano-particles (MNP's). However, unlike in metallic nano-particles where electron gas is set to oscillation by impinging the EM quasiparticle (plasmon), in case of SSPP waveguide near terahertz (THz) EM waves themselves resonate in the cavities and then the cavities are coupled through transversal dielectric medium as shown in Fig. 5. There are three distinct modes of SSPP signal propagation which are delineated in Fig. 5 as Symmetric, Anti-symmetric and Resonant modes, and their dispersion characteristics are plotted with respect to wavevectors. Clearly, it can be seen that both Symmetric and Anti-symmetric modes are attenuated, and only the Resonant mode SSPP waves are transmitted if the appropriate biasing voltage is applied to LCD dielectric medium. The Q-factor of Resonant mode is 1000 times better than the other two modes. Further consideration is given for practical implementation of the Objective 6. For example, we consider the delay-bandwidth product for an efficient switching device, the switching speed issue of liquid crystal, the inherent attenuation factor, insertion losses, and device implementation issue.

During the current year, we have also *partially* demonstrated the Objective 7. Specifically, we have developed a new design concept to increase the photo-generation rate in a small active domain by using sub-wavelength structures consisting of surface plasmon photonic crystal slab (SPPCS) acting like a near field generator and an antireflection coating. The polarizability of rectangular metallic cylinder predicts surface plasmon (SP) resonance frequency in the SPPCS photodiode. Thus, the enhanced near field intensity arising from SP resonant oscillation has a potential to solve the low photo-generation

problem. In addition, photonic band structure dramatically changes TM photonic maps with extraordinary transmission and low reflection, thereby leading to an efficient nano-photodiode (Fig. 6).

We have now also developed a fully operative Rigorously Coupled Wave Analysis (RCWA) analysis as discussed here. First, we have calculated the polarizability of the rectangular metallic cylinder to obtain surface plasmon (SP) resonant frequency for an efficient near field EM confinement in the semiconductor layer. Physically, when the wavelength of the incident field is large compared to the geometry of the metallic rectangular cylinder, the confined electron cloud generates the dipole-like polarization, thus explaining the surface plasmon resonance in the 2D rectangular geometry. This polarizability of the rectangular metallic cylinder placed at free space ($n=1$) is given by

$$p_L = -8\chi ab(C_1 - C_2(a^2 - b^2))$$

where χ is the electric susceptibility given by $\chi = (\epsilon_m - 1)/(4\pi)$, $\epsilon_m(\omega) = \epsilon_r(\omega) + j\epsilon_i(\omega)$ is the complex dielectric function of metal, $C_1(\epsilon_m, a, b)$ and $C_2(\epsilon_m, a, b)$ are function of ϵ_m , a and b .

Fig. 7(a) shows the magnitude of dimensionless reduced polarizability $2\pi|p_L|/b^2$ for rectangular SP cylinder ($a=25$ nm, $b=25$ nm) by using the Johnson's experimental data of three different noble metals: Cu (copper), Au (gold) and Ag (silver). As can be seen, compared with Cu and Au, Ag shows the maximum polarizability, thus generating strong EM field enhancement. However, the imaginary permittivity of Si tremendously increases from 3.0 eV, thus the resonance frequency (3.49 eV) of Ag rectangular cylinder lies in the strong damping region. Therefore, we choose Au to minimize far field damping loss in the semiconductor medium at the resonant condition (2.36 eV) and obtain the efficient delocalized SP modes at the lower frequency. In Fig. 7(b), the magnitude of polarizability of Au cylinder can be manipulated by changing a (width) and b (height). As the ratio ($r=a/b$, b is 25 nm) decreases, the magnitude of polarizability of Au also decreases because of the capacity of electron cloud inside the metallic cylinder.

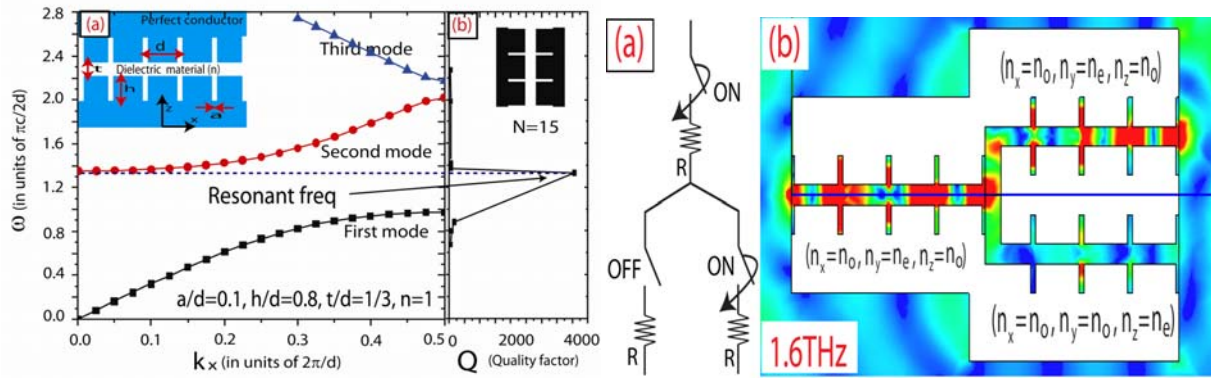


Fig. 5: The SSPP waveguide has three distinct modes as shown in the Left diagram. The First mode is called the Symmetric mode where the frequency rolls off as wave vector increases along x axis. The second mode is called the Resonant mode since the cavities in the SSPP waveguide match the THz wave propagation and the SSPP signal propagates longitudinally with high (~ 3800) Quality factor as shown for a 15 groove structure. The third mode is called Anti-symmetric mode which is also fully quenched in the SSPP waveguide. In the Right diagram, FDTD simulation results of SSPP signal propagation through the waveguide are illustrated by allowing the waveguide to act as a 2:1 Mux or a Y splitter, where signal can

be steered through the upper or lower arm of the splitter by applying appropriate voltages to different segments of the LCD. This opens the possibility of building dynamically controlled buses for microprocessors and als THz Boolean logic circuitry.

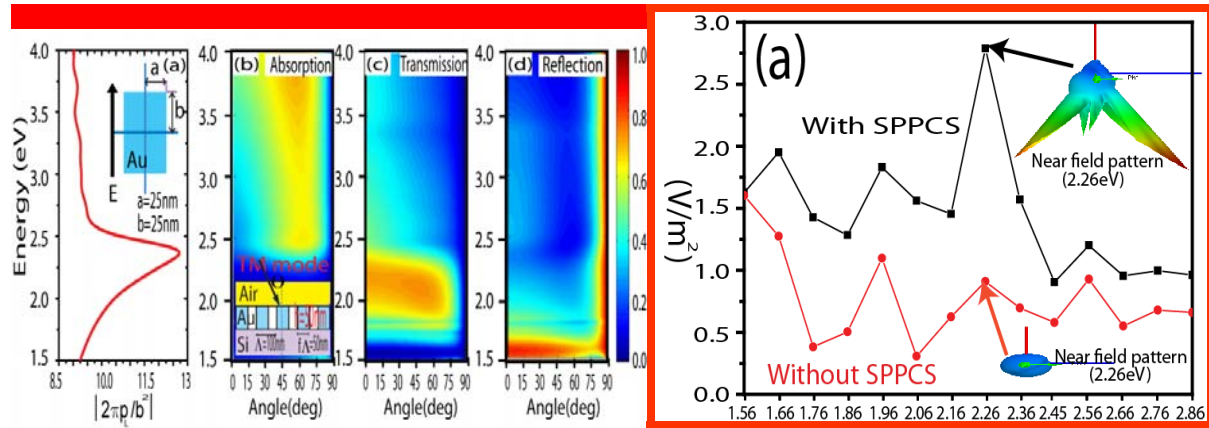


Fig. 6: The photodiode is augmented by creating one-dimensional grating structure as shown in the Left diagram where the anti-reflection coating of the photodiode was replaced by periodic structure. The dimension of the structure is carefully selected to concentrate the photon flux at the P-N junction of the photodiode by utilizing the near-field property of surface Plasmon waves. As a result, a large volume of additional photon flux concentrates near 2.5 eV as shown by yellow color in the middle Transmission column, while very little energy is reflected out as shown in the Reflection column. This near-field assisted generation of electron-hole pairs enhances the efficiency of photonic detectors that can be used in a wide variety of applications ranging from tiny efficient photonic detectors to large-area solar cells to generate carbon-free Green energy.

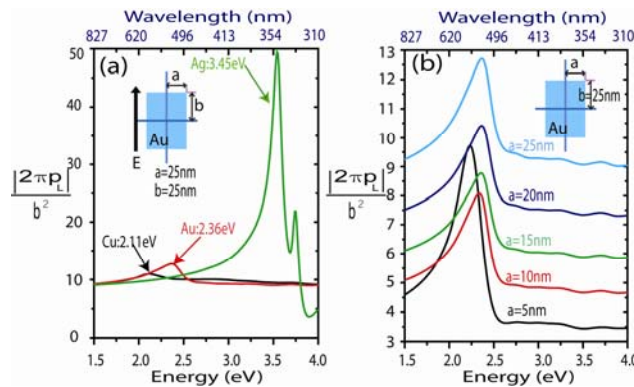


Fig. 7. (a) Dimensionless reduced polarizability of rectangular SP cylinder as a function of photon energy. These curves are obtained from the cubic spline method by using the Johnson's experimental optical data of three different noble metals: Cu, Au and Ag. (b) Dimensionless reduced polarizability of Au rectangular cylinder with different geometry ratio (a/b)

Extension Year: September 2010 – December 2010

During the last 4 months of the extension period, planning has been made for fabrication of SSPP structures in a continuing AFOSR grant which will be submitted as per the following planning.

In order to verify the THz technologies, spoof surface plasmon polariton (SSPP) waveguides will be fabricated in the continuing activity under the supervision of Pinaki Mazumder and his colleague, Jack East by using micromachining technology. It may be noted that both MNP chains and MNW's have been fabricated by other researchers like Brongersma and Atwater to demonstrate that surface plasmon (SP) can be used to transmit data at optical frequency using nanoscale structures. However, dynamically controlled SSPP waveguide designs that will be pursued by Mazumder and East require proof of concept demonstration to validate the design methodology proposed by Song and Mazumder in the paper[8]. The major advantage of our approach is submicron in plane dimensional control. This can allow accuracy beyond the ability of conventional machining. Batch fabrication will allow low cost fabrication of many components at the same time. However, there are limitations. The associated etching can easily occur in only one direction. Careful design and possibly new geometries will be needed to obtain the required electrical properties with this approach. Within these limitations the SSPP structure is almost ideal. An example of the dimensional control possible with this process is shown in Fig. 8.



Figure 8. Micromachined 75-110 GHz Waveguide Transition

The section on the right is the cross section of a WR10 wavguide and the structure on the left is part of an H field broadband transition. The dimension control is easily on a micron scale, much better than conventional machined waveguide. We have also developed a process technology to obtain an etch depth accuracy of $\pm 2 \mu$. Our approach will be based on an E plane geometry to best use the advantages of the etching for SSPP fabrication.

The tools needed for the fabrication include photoresist and optical lithography to pattern an etch mask on a silicon wafer, an STS DRIE (Deep Reactive Ion Beam Etcher) to etch vertical patterns into the wafer, an Enerjet sputtering metal deposition vacuum system to deposit conductor metals and a SUSS SB6E thermal wafer bonder to gold to gold bond fabricated structures together. This equipment, along with the Interserv pattern generator to make the lithography masks, is available in the Lurie Nanofabrication Laboratory at The University of Michigan. Devices with nearly 1.5 THz center frequency and scaled devices with a 270 GHz center frequency will be fabricated. The scaled structures will be measured with OML WR3 waveguide test sets that are available in The Radiation Laboratory at The University of Michigan.

A novel process approach has been developed to realize the E plane SSPP structures. A very short summary of the process is shown in Fig. 9 below.



Figure 9 (a) Initial Configuration (b) Final Structure

The starting wafer is a special silicon on oxide or silicon wafer from an outside vendor. The silicon layer thicknesses can be specified to $\pm 2 \mu$. The top silicon wafer thickness corresponds to $\frac{1}{2}$ the desired

waveguide large dimension. The bottom layer thickness is not critical. The yellow oxide in the figure is 1 μ thick. East and Mazumder have developed a multimask etching process to realize multiple etches into silicon with precise dimension control. The structure in Fig. 8 is an example. Two lithography and etch mask step are used to pattern the wafer. The resulting etches are the red and blue regions in Fig. 9 (a). The layers are required to be selective to different etch gases. In this case, photoresist and oxide were used. A silicon etch with the blue mask is used to etch a portion of the way to the buried oxide layer. The desired waveguide region is protected in this etch. The blue mask is then removed and the etch continues with a chemistry designed for the red mask. Since the outside region has already been etched this second etch will reach the oxide etch stop on the outside while the waveguide region will still be protected. The outside oxide can be removed and the etch continued until the waveguide side oxide is exposed. The resulting is shown in Fig. 9 (b) with cross-section dimensional control defined by lithography and vertical control defined by wafer thickness. The initial prototype structures will be fabricated for the 220-325 GHz frequency range. Notice that the process can easily be scaled to higher frequencies. In fact, the process becomes easier because the etch depths and resulting etch control requirements are reduced. Further studies will be made and explained in the proposal for the continuing grant.

List of Publications:

1. P. Mazumder, "Applications of Quantum Dots in Nanoelectronics and Plasmonics," *Proceedings on IEEE Conference on Nanotechnology*, Cincinnati, July 2006.
2. K. Song and P. Mazumder, "Surface Plasmon Dynamics of a Metallic Nanoparticle," *Proceedings on IEEE Conference on Nanotechnology*, Hong Kong, Aug. 2007.
3. K. Song and P. Mazumder, "Modeling of Metallic Nano Particles for SPICE-Compatible Equivalent Circuit," *Proceedings of Nanoelectronic Devices for Defense and Security Conference*, Crystal City, June 2007.
4. K. Song and P. Mazumder, "An Equivalent Circuit Modeling of an Equispaced Metallic Nanoparticles (MNPs) Plasmon Wire," *IEEE Transactions on Nanotechnology*, vol. 8, pp. 412-418, May 2009.
5. K. Song and P. Mazumder, "The Guiding Mechanism of Nonradiative Surface Plasmon (SP) Energy Transfer along the Metallic Nanowire," *Proceedings on IEEE Conference on Nanotechnology*, Dallas, Aug. 2008.
6. K. Song and P. Mazumder, "Equivalent circuit modeling of non-radiative Surface Plasmon (SP) energy transfer along the metallic nanowire (MNW)," *IEEE Transactions on Nanotechnology*. (already available in IEEE Xplore, though the paper version has not been scheduled yet).
7. K. Song, and P. Mazumder, "One Dimensional Surface Plasmon Photonic Crystal Slab (SPPCS) for a Nano- photodiode" *IEEE Transactions on Nanotechnology*.
8. K. Song, and P. Mazumder, "Active Terahertz Spoof Surface Plasmon Polariton Switch Comprising the Perfect Conductor Metamaterial" *IEEE Transactions on Electron Devices*, vol. 56, no. 11, pp. 2792-2799, 2009.
9. K. Song and P. Mazumder, "Active Tera Hertz (THz) Spoof Surface Plasmon Polariton (SSPP) Switch Comprising the Perfect Conductor Meta-Material," *Proceedings on IEEE Conference on Nantechnolog*, Genoa, Italy, Aug. 2009