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Plasmonics based VLSI processes

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Abstract

In continuum to my previous paper titled 'Implementation of plasmonics in VLSI', this paper attempts to explore further, the actual physical realization of an all-plasmonic chip. In this paper, various methods of plasmon-based photolithography have been discussed and an observation is made w.r.t the cost effectiveness and ease of adaptability. Also, plasmonics based active element has been discussed which would help unravel further arenas of approaches and methods towards the realization of an all-plasmonic chip.

Keywords

Waveguide Ring Resonator, photolithography, plasmons, sub-wavelength.

1. Introduction

Surface plasmon polaritons (SPP) have proved to be very efficient in localizing and guiding of photonic signal on a scale which is hardly reachable with conventional dielectric waveguides. This makes them an important tool for minimization of integrated optical circuits. A surface plasmon polariton is an electromagnetic wave coherently coupled to electron oscillations and propagating in a wave-like fashion along a metal–dielectric interface [1]. To construct a fully functioning active photonic circuit, with provision for signal guiding, multiplexing and processing, inevitably active plasmonic components need to be added in the system. However, the problem with this approach is that, available non-linear materials provide rather small refractive index changes. The major disadvantage of which is the low confinement of light and the subsequent leakage. To overcome this limitation, Dielectric Loaded SPP waveguides (DLSPPW) based Waveguide Ring Resonator and Bragg Reflector have been developed.

Optical (Photo) lithography is one of the most integral and important processes in modern micro-fabrication technology in the recent years.

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Advances in this field have improved conventional photolithographic techniques so far restricted by diffraction limit. The following are some of the plasmonic photolithographic processes and active elements that would prove to be a huge step forward towards developing**.**

2. Waveguide Ring Resonator

A waveguide ring resonator is a highly selective passive element for wavelength selection. It is produced by placing a waveguide loop in the vicinity of a straight DLSPP waveguide. It has been proven both theoretically and experimentally that WRR is a highly efficient passive element for wavelength selection. Due to the coupling between two nearby waveguides, some of the input mode S0 propagates further in the straight waveguide, but some L0 is transferred to the ring (see inset to Fig. 1a).

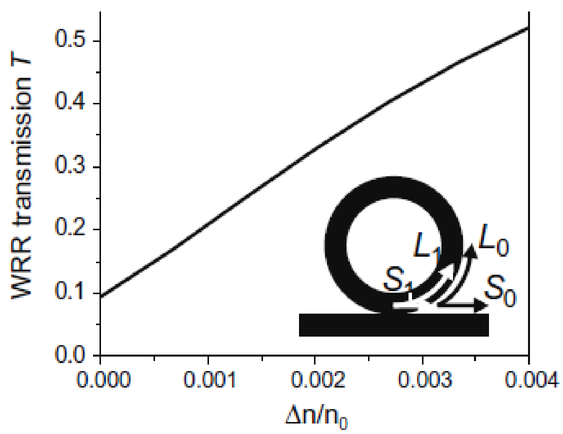

Fig 1: Active WRR element: transmission as a function of the refractive index change in the ring material. Inset shows redistribution of SPP partial waves [1]

Once the mode L0 has completed one round trip in the ring, the inverse process happens. Part S1 of the ring mode is coupled back into the straight section, interfering with S0 and the rest L1 continues to propagate in the ring interfering with the initial ring mode. The same redistribution happens after each cycle: L1 to S2 + L2 to S3,... .[1]

In the above , a quite complicated output interference pattern is obtained. However, final outcome lies within a range of maxima and minima. Transmission is minimum when: the wave initially passes through S0 and the sum of all the waves decoupled from the ring R = S1 + S2 + . . . are out of phase [1]. Transmission is maximum when: the optical path of the mode in the ring is half a wavelength longer or shorter, then the S0 and R are in phase [2]. Thus, it can be observed that SPP transmission wavelength is mainly dependent on the radius of the ring. Here, gap size is the determining factor for a strong contrast in the transmission ie, transmission of a minima or a maxima. The good contrast is of essence as it defines the coupling strength and thus all the amplitudes of the interfering waves. Proper adjustment of gap size is done such that for minimum transmission, S0 and R and out of phase but of equal amplitudes.

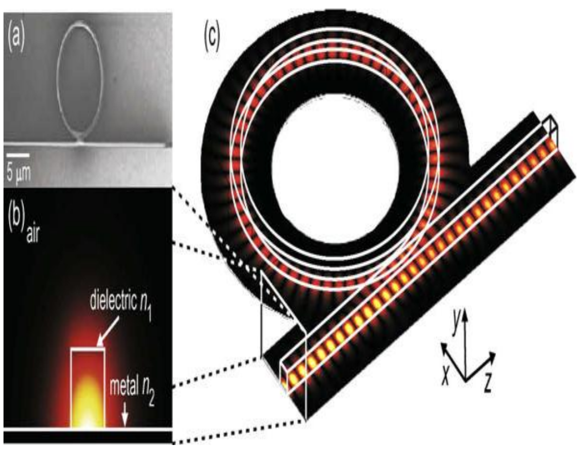

Fig 2: (a) SEM image of the DLSPP Waveguide Ring Resonator fabricated by deep ultraviolet lithography [3]. (b) Crossection of 600 _ 600 nm DLSPP waveguide and abs (Ey) field profile of a fundamental TM00 SPP mode in it. (c) Full 3D FEM numerical simulation of ring resonator, the field map represents the absolute value of the electric field component perpendicular to the metal abs (Ey) at the metal surface [3]

Depending on the phase gained by the mode propagating around the ring, the outcome is obviously dependant on the wavelength. While scanning through h wavelength a sharp transmission resonance is observed: wavelength difference between full and zero transmission can be as small as 15 nm. Note that the ring radius sufficient for such good Wavelength selectivity is just _5.5 micrometer, corresponding to the device Size of just 11 micrometer. At a fixed ring radius and fixed gap between the waveguides it depends on the effective refractive index of the mode in the ring, which in turn is defined by the refractive index of the material. This leads to the idea of fabricating the ring from non-linear optical material, the optical properties of which can be changed by external stimulation, and through this modulate the transmission of an SPP wave [1].

3. Sub-Wavelength Photolithography

Photolithography is the process of transferring a pattern on the bulk substrate using UV light. For further miniaturization of circuits the critical dimensions need to be minimised even further than the diffraction limit. The minimum critical dimension (half-pitch resolution) achievable by photolithography (Optical projection lithography) is given by

$$CD_{half\,pitch} = k_1 * \lambda / NA \qquad (1)$$

where λ is the incident source wavelength, *NA* is the numerical aperture of projection optics of the system and *k1* is a constant value as a indication of the effectiveness of the wavefront engineering techniques [3]. From the equation, we can observe that to reduce the half-pitch resolution either we have to reduce the wavelength of the light source or the numerical aperture of the projection system. In effect, we need shorter wavelength laser sources. But due to unavailability of suitable ultraviolet laser sources various techniques have been suggested.

Extreme UV lithography: the illumination wavelength is reduced to the extreme UV (smaller wavelength) to get smaller features [3].
Immersion lithography: numerical aperture of the imaging system is increased by inserting high index fluids (prism or liquid) between last optical component and wafer surface. But this technique is either limited by air absorption or availability of high index fluids[3].
Imprint lithography: Nanometer scale features are achieved by stamping a template on a thin polymer film and it can also generate sub-50nm features by integrating laser beam with AFM, NSOM and transparent particles. The main disadvantages of this technique are: (i) problems with the imprint template and substrate during the printing process with regards to levelling, which determine the uniformity of the imprint results, and (ii) slow process speed, which limits their applications in industry [3].
Laser interference lithography (LIL): It can be used to fabricate high speed and large area period nanostructures. The basic principle is the interference of coherent light from a laser source to form a

horizontal standing wave pattern in the far field, which can be recorded on the photoresist [3].

Scanning probe lithography: In this the Scanning Tunneling Microscope (STM) or Atomic Force Microscope (AFM) can be used in gap between an AFM or an STM tip by introducing a laser beam to pattern nanometer scale features, and also substrate surface with tip scanning over the surface. But they have stringent limitations with respect to certain materials and effectiveness applies only for certain ambient conditions[3].

Evanescent wave lithography (EWL): It is one of the near field interference lithography technique to achieve nano-scale feature at low cost. when two resonantly enhanced, evanescently decaying wave are superimposed, shorter wavelength intensity patterns can be created in the near field of diffraction grating or prism. Inspite of providing a good resolution, low contrast and short exposure depth put limitations in this method.

These problems can be subdued to a great extent by surface plasmon resonance phenomena due to their characteristics of enhanced transmission in the near field[3].

Thus, the above discussed methods, though providing photolithography at sub-wavelength dimension, are fraught with inherent limitations making them difficult to adapt in the current VLSI scenario.

4. Plasmonic Lithography

Plasmonic lithography is an emerging area of near field photolithography technique which overcomes the barrier of diffraction limit and enables nano resolution features to be fabricated beyond the diffraction limit at low cost.

Surface plasmon polaritons are electromagnetic waves that propagate along the surface of a metal. Due to the large enhancement of the evanescent field at the metal/dielectric interface, surface plasmon resonances in metallic films are of interest for a variety of applications.

Gap Modes in metal-particle system:

At the nanoscale, mainly electric oscillations at optical frequency contribute the optical fields, but the magnetic field component does not contribute significantly due to weak field component. Such fields have the ability to concentrate and support the nanostructured material due to the existences of localized optical modes on dimensions much smaller than the optical wavelength. The elements that cause these energy concentrations are called surface plasmons (SPs). To support surface plasmons a system should contain both negative and positive dielectric permittivities. Among other things, for surface plasmon resonance to occur, the shape of the metal nanoparticle and metal surface thickness is an important factor.

A thin metal surface is associated with surface plasmon polariton (SPP) modes, which are coupled modes of photons and plasmons. Since the SPP modes are nonradiative electromagnetic modes, to excite them the incoming beam has to match its momentum to that of the plasmons [4]. The LSP modes are radiative electromagnetic modes and hence can be excited directly by incident photons. So, when a system consisting of a fine metal particle is placed near to a metal surface, an electromagnetic interaction between LSP modes associated with metal nanoparticle and SPP modes associated with metal surface is possible. This interaction plays an important role to enhance the light emission from metal-insulator-metal tunnel junction, mediated by metal nanoparticles. Due to this electromagnetic interaction there exist new types of localized electromagnetic normal modes, called gap modes in the space between the nanoparticles and the surface.

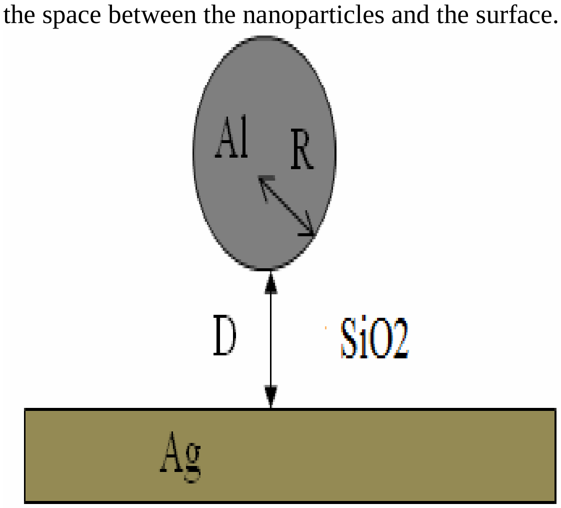

Fig 3: Schematic diagram of the metal particle-surface system: Al Nano Sphere of radius R is placed at a distance D from the Ag surface [3]

Figure 3 represents an isolated metal sphere (Al) of dielectric function ε (ω) embedded in surrounding medium (SiO2) of dielectric function *m* ε , is placed close to a metal surface (Ag). The retardation effects of electromagnetic fields can be neglected when the radius (R) of the sphere is small and resonant frequencies corresponding to the excitation of LSP are expressed by

$$\varepsilon(\omega) = -\varepsilon_m (l + 1)/l \quad (2)$$

where l = 1,2,.... is an integer. If the sphere is much smaller than the wavelength of the incident light, the dipole mode with l = 1 is mainly excited. To make this concept a little more lucid we can approximate the LSP modes as a dipole and consider its interaction with image dipole induced inside the metal surface. The LSP mode is majorly modified by this dipole-dipole interaction, thus affecting the resonance frequency and field distribution. To put it in another way, change of symmetry causes new electromagnetic modes to appear. It means the spherical symmetry of the isolated sphere translate to cylindrical symmetry for a sphere-surface system. These modes also correspond to polarization modes parallel and perpendicular to the symmetry axis [3]. When the particle-surface distance is sufficiently small (D/R<1), this system can support a series of gap modes and the electric field becomes more and more localized at the gap between the particle and the surface. When the gap mode is excited, the intensity of the electric field is enhanced relative to that of the excitation field and these modes are believed to play an important role in the light emission process. It is reported that the maximum enhancement factor is larger than that achieved with an isolated particle (LSP excitation) or a surface alone (SPP excitation) system [3].

5. Conclusion

Thus, plasmon based active devices like Waveguide Ring Resonator prove that construction of more such elements is indeed possible. In constructing nanoscale chips, nanoscale lithography is the obvious requirement. Even though other techniques can be used to achieve sub-wavelength, nanoscale level lithography, plasmonic lithography is the most desirable option available, as it is both cost effective and easy to adapt within the current VLSI framework. From the above discussion, we can see that plasmonic active elements and plasmonic lithography are a huge step forward on the path towards developing an all-plasmonic chip. The potential advantages of such a device are, of course, huge; ranging from increasing processing speeds by atleast 10^5 times to miniaturization of circuits, a new era in the VLSI industry is well on its way.

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