Plasmonics with Nanostructure Materials

JAGMEET SINGH and S S VERMA
Department of Physics, S.L.I.E.T., Longowal, Distt.-Sangrur (Punjab)-148 106.
Email: ssverma@fastmail.fm

A surface plasma wave (SPW) is an electromagnetic wave that propagates at the boundary between two media with different conductivities and dielectric properties. Present paper will discuss the modeling of surface plasma wave propagation characteristics as a function of input signal energy for different materials (i.e., medium of propagation) at nano scale dimensions.

Key Words: Surface plasma waves, plasmons, Plasmonics, Modeling

INTRODUCTION

Plasmonics is the science, technology and application of plasmons to carry information, which is the collective oscillation of a free electron gas (plasma). Plasmons are mainly found in metals and often at optical frequencies.Pines[1] theoretically described the characteristic energy losses experienced by fast electrons traveling through metals and attributes these losses to collective oscillation of free electrons in metals and called these oscillations as plasmons. Ritchie[2] has observed for a semi-infinite plasma that there exists not only bulk plasma oscillation of frequency (ω_p) in interior of plasma, but also surface plasma oscillation, the quanta of which is called surface plasmon at the interface of medium and vacuum (dielectric) whose frequency (ω_{sp}) is $\omega_p/\sqrt{2}$. Further, the excitation of plasmon by optically and fast incident electrons along with the effect of oxide coating on surface for different materials is investigated by many researchers[3-6].

Presently, metal nanostructures have attracted researchers[7-9] both fundamentally and technologically because of their exotic physical and chemical properties suitable for wave propagation and nano-plasmonic optical properties and their applications are discussed. Different plasma excitation methods like passing an electron through materials or by reflecting an electron or a photon from a film can be used[10]. This reflected or transmitted electron or photon shows an energy loss equal to integral multiple of plasmon energy. Thus, the generated plasmon energy may be used to transfer the data along the surface of the materials by using appropriate technique. The transfer of energy along the surface depends on the properties of the materials like thickness of the medium, temperature, refractive index, electron concentration and effective mass etc. In the present paper, surface plasma wave (SPW) propagation has been studied in different material medium as a function of input energy signal.

THEORY

For a unit volume electron gas of concentration (n), the input energy signal is applied to structure which disturbs the quasi-neutral plasma medium, as a result electron gas is displaced from equilibrium position as a whole with respect to the fixed positive ion background. Thus, the electric field is developed in such a direction so as to restore the neutrality of plasma during generated electron vibrations with a characteristic frequency called plasma frequency. For a simplest model of electron vibrations (simple harmonic motion) in the medium it is assumed that there is no magnetic field, no thermal motion, ion are fixed in space in uniform distribution and electron motion occurs in one direction only. Since this is a one dimensional problem, Gauss theorem gives the electric field experienced by the electrons to be = neu/ε_0 . The equation of motion of electron gas is: $n\,m\,d^2u/dt^2 = -neE$ (1)

$d^2u/dt^2 + \omega_p^2\,u = 0$ (2); where, $\omega_p^2 = ne^2/m\varepsilon_0$ is plasma frequency[10] and other symbols have their usual meanings.

Frequency of SPW is given by $\omega_{sp} = \omega_p/\sqrt{2}$ over a medium bounded by vacuum (derived from the boundary condition[10] that normal component of displacement current be continues at the boundary requires $\varepsilon(\omega) = -1$). It is mentioned[13] that propagating surface plasmons are the quanta of collective plasma oscillation localized at the interface between a metal and a dielectric, provided the thickness of the metal film exceeds the plasmon skin depth, oscillations at each metal dielectric interface are decoupled, and independent surface plasmon modes at each metal-dielectric interface are sustained. SPW propagates along metal surface until decays by absorption or converted back into a photon or phonon.

Simulation technique

Second order differential equation (2) representing plasma dispersion relation is simulated making use of single-step 4th order Runge-kutta method. While developing simulation technique it is assumed that input energy devolpes electric field (calculated electrostastically with $E=\sqrt{(2energy/\varepsilon_0)}$[12] from which initial displacement of electron gas and then initial velocity of electron gas are calculated. Further position, velocity variations and then frequency of electrons gas oscillation are calculated. Approximate time-step value is determined from initialization of velocity of electron wave and displacement calculations and then fixed through further hit & trial.

Selection of materials

Materials like Silver, Copper, Aluminum, InSb (Indium Antimonide) and Beryllium are chosen in the present study. Ag, Cu and Al are selected because they are commonly used metals in electronic circuits. Insb (a dielectric material) is selected to observe metal-vacuum interface or dielectric-dielectric interface.

Beryllium is selected to change metal to alkaline earth metals well-characterized for their homologous behavior. The electron densities for Ag, Cu, Al, InSb, and Be are 5.85x10^{28} m^{-3}, 8.45x10^{28} m^{-3}, 18.06x10^{28} m^{-3}, 4.0x10^{24} m^{-3} and 24.2x10^{28} m^{-3} respectively[10] and thus, the calculated surface plasmon frequencies ($\omega_{sp}=\omega_p/\sqrt{2}$)[10] for these materials are 0.964x10^{16}, 0.116x10^{17}, 0.169x10^{16}, 0.797x10^{14}, 0.196x10^{17} respectively.

Input energy range

Input energies are selected as 10 eV, 12 eV, 15 eV and 20 eV (in the range 10-20eV) because the valence electron density in solids ranges from 10^{28} to 10^{30} so the corresponding plasmon excitation energy varies from 4 eV to 30 eV[1]. Our interest is to transport the signal of any energy by surface plasmon wave and not in their minimum or maximum energy requirement for excitation; hence, lowest or highest energies for excitation are of least interest.

RESULTS AND DISCUSSION

Figure 1 for copper show that when input signal energy is 10eV, Surface Wave Frequency (SWF) becomes equal to Surface Plasmon Frequency (SPF) for a distance of ≈ 84nm and then decays. For a signal of 12 eV after a distance of ≈ 72 nm SWF becomes equal to SPF where as for 15 eV SWF comes equal to SPF at distance ≈ 84nm and as it moves further there are some fluctuations and it tends to raise again near to SPF at a distance ≈ 300nm. When input signal energy is 20 eV SWF becomes equal to SPF at a distance ≈ 81nm then decays. In fig. 2 for aluminum, with input signal energy of 10 eV SWF can survive with SPF from distance ≈ 114nm to ≈ 296 nm after that its frequency reduces. With input signals of 12 eV, 15 eV and

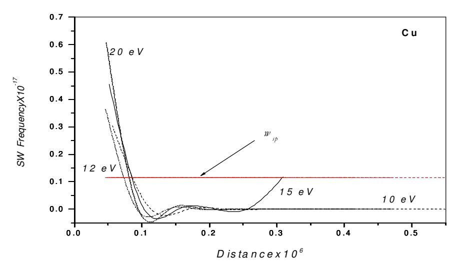

Fig.1. Variation of SWF for Copper

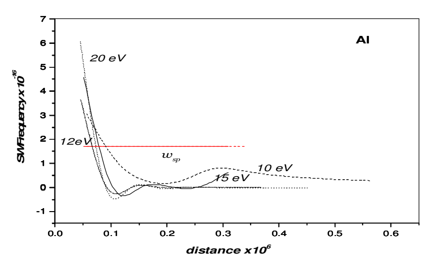

Fig.2. Variation of SWF for Aluminum

20eV, SWF becomes equal to SPW after distances of ≈ 75nm, ≈ 87nm and ≈ 80 nm respectively but it does not survive in any case and its frequency reduces immediately. With Silver as a medium, Fig. 3 shows that when input signal energy is 10 eV SWF survives as SP wave from ≈ 112nm to ≈ 294nm while with signal energy of 12 eV, 15eV, 20eV SWF is equal to SPF at ≈ 74 nm, ≈ 87nm, ≈ 80nm respectively and after that it decays.

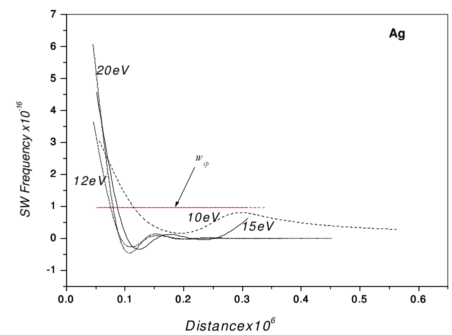

Fig.3. Variation of SWF for Silver

According to Fig 4 for InSb, when input signal energy is 10 eV the surface wave survive as SP wave from a distance ≈ 142 to ≈ 650nm because in this range SWF is equal to SPF. While input signal energy of 12 eV surface waves can play a role of SP wave from ≈ 143nm to ≈ 239nm & after that its frequency reduces. When input signal energy is of the order of 15 eV and 20 eV then SWF becomes equal to SPF at distance ≈ 180nm and ≈ 133nm respectively and then its frequency decays. Figure 5 shows it for Beryllium and indicates that when input signal energy is 10eV, 12eV the SWF becomes equal to SPF at distance ≈ 82nm for both signals, with input signal energy of 15eV SWF becomes equal to SPF at distance ≈ 82nm and from graph it is clear that it is maintained up to a distance ≈229nm, with input signal of 20 eV SWF equals to SPF at distance ≈ 75nm but it is not further maintained and reduces.

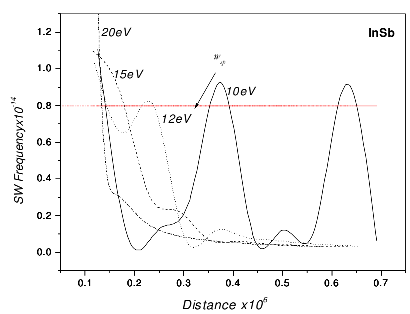

Fig.4. Variation of SWF for InSb

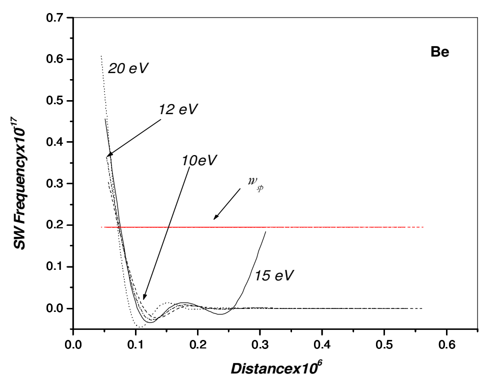

Fig.5. Variation of SWF for Beryllium

Conclusions

From the present simulation studies on plasma wave propagation with different input signal energies through different material medium, it is concluded that:

- For Cu & Be the input energy required to make SPW to survive the best option is 15eV where as for other mediums like Al, InSb and Ag this value comes to be about 10eV. It is found that the surface wave frequency never comes at par with the surface plasma wave frequency if the former is less initially.

- Plasmonics survival propagation distance for all materials under investigation was calculated to be in the range of 200nm where as for InSb it came about 500nm within a suitable waveguide. Thus, dielectric-dielectric (presently vacuum) interface is better medium for plasmonics as compared to metal-dielectric (vacuum) under similar conditions.

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