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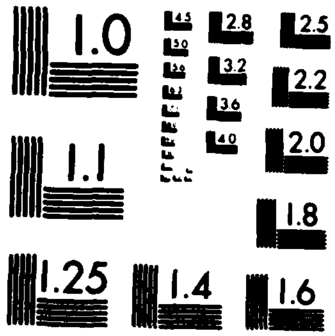

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Final Technical Report
May 1987

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ACOUSTIC PHONONS, SURFACE PLASMONS AND SURFACE ACOUSTIC PLASMONS IN A SUPERLATTICE AND THEIR NONRECIPROCAL DEVICE APPLICATIONS

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John S. Derov

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441-5700

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The literature was surveyed to determine potential applications of acoustic and plasma phenomena in superlattices. The use of folded zone acoustic phonons and acoustic surface plasmons in III-V compounds like AlGaAs/GaAs superlattices is addressed. A dielectric phonon filter is presented and an acoustic resonator is considered. Surface plasmons and surface acoustic plasmons are discussed and a transducer, delay line and mixer are proposed as applications. A 500-GHz isolator utilizing surface magnetoplasmons is also presented.

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Acoustic Phonons, Surface Plasmons, and Surface Acoustic Plasmons in a Superlattice, and Their Nonreciprocal Device Applications

1. INTRODUCTION

The primary concern of this investigation was to look at acoustic and plasma phenomena in superlattices and determine if there are any possible device applications. The acoustic phenomena addressed in this investigation were acoustic phonons in an undoped superlattice, acoustic phonons in a periodically doped superlattice, and surface acoustic plasmons in a periodically doped superlattice. This report has two parts. The first part deals with the acoustic phonon phenomena and the second part deals with surface plasmons and surface acoustic plasmon phenomena.

2. ACOUSTIC PHONONS

2.1 Single Crystal Lattice and Superlattice Structure

With the development of molecular beam epitaxy (MBE) came the ability to grow very thin layered crystalline materials. These thin layers can be on the order of a monolayer in thickness (approximately 1 to 10 Å thick). This stimulated the development of crystal structures consisting of different material layers, such

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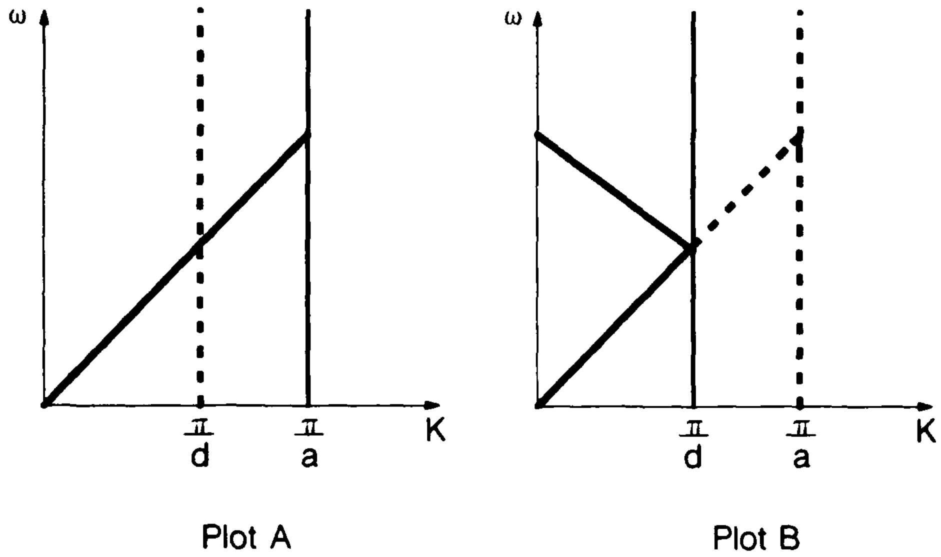
as gallium arsenide (GaAs) and aluminum arsenide (AlAs). A material of this type is known as a superlattice. A single layer thickness can be on the order of several hundred monolayers. The layers of GaAs and AlAs are repeated several times giving the superlattice a spatial period. The length of the period is equal to the total thickness of a GaAs and an AlAs layer. Though the period is larger than an atomic lattice distance, it causes an expansion of the unit cell.

The unit cell[1] is defined as the minimum volume that fills all space under the proper lattice translations and contains one lattice point. The simplest unit cell to consider is a cube in a simple cubic lattice. Since all the sides of the cube are equal, their length can be defined by a constant. This constant is known as the lattice constant 'a' and it is also the nearest neighbor distance for the simple cubic lattice. The simple cubic lattice has another convenient property. It is cubic in both cartesian and reciprocal lattice space. Reciprocal lattice space is the representation of the lattice in k-space. If the cubic unit cell is a Wigner-Sietz cell in cartesian space, it becomes a Brillouin zone in reciprocal lattice space. The boundary for the Brillouin zone is $-\pi/a \leqq k \leqq \pi/a$, which comes from the transformation of the lattice constant a into reciprocal lattice space.

In the superlattice the period 'd' of the superlattice is equivalent to the lattice constant 'a' for the simple cubic lattice. Thus the unit cell is expanded to the distance d, the period of the superlattice. The phonon dispersion is affected by the expansion of the unit cell. Increasing the length the unit cell generates new phonon branches in the crystal. A phonon is the quantized energy of a lattice vibration or elastic wave. This is analogous to the photon that is the quantized energy of an electromagnetic wave. When the new phonon dispersion is plotted in k-space the phonon branches fold back along the unit cell boundary π/d, where 'd' is the period of the superlattice. Thus, the folding back generates new phonon branches. A conceptual acoustic dispersion relation is shown in Figure 1 for a single crystal or an infinite lattice and a superlattice. The folding back creates a degeneracy in the phonon modes allowing more than one frequency to have the same wavelength.

1. Kittel, C. (1971) Introduction to Solid State Physics 4th Ed., John Wiley & Sons, Inc., pp. 1-199.



PLOT A. Plot A is the dispersion for an acoustic phonon branch of a single crystal. The unit cell boundry is given by π a. where "a" is the nearest neighbor distance for a single crystal lattice. Superimposed on the single crystal dispersion is the boundry for a superlattice π d

PLOT B: Plot A is the folded back dispersion of an acoustic phonon branch for a superlattice. The unit cell boundry is given by π d where "d" is the period superlattice. The folded back portion of the branch would normally extend to the π a boundry as in plot a .

Figure 1. Acoustic Phonon Dispersion for a Single Crystal and a Superlattice

2.2 Acoustic Phonons in a Superlattice

The alternating layers of a superlattice that cause the folding back of the phonon branch,[2] stimulated the investigation of high frequency acoustic phonons. Early work was done by V. Narayanamurti et al,[3] who investigated the alternating

2. Baker, A., Merz, J. L., and Gossard, A. C. (1978) Study of zone-folding effects on phonons in alternating monolayers of GaAs-AlAs, Phys. Rev. B, 12(No. 8):3181-3196.

3. Narayanamurti, V., Stormer, H. L., Chin, M. S., Gossard, A. C., and Wiegmann, W. (1979) Selective transmission of high-frequency phonon by a superlattice: the dielectric phonon filter Phys. Rev. Lett., 43(No. 27):2012-2016.

layers of a GaAs and aluminum gallium arsenide (AlGaAs) superlattice for high frequency phonons. Their work compared theory and experiment for a GaAs/AlGaAs superlattice as a stop band "dielectric phonon filter". The filter works on the simple principle of selective phonon reflection. The reflection of the acoustic phonons propagating normal to an interface of two elastic media with different acoustic impedances Z_1 and Z_2 is analogous to the reflection of photons at the interface of two optical media with different indexes of refraction. The stop band wavelength for the phonons must satisfy the Bragg condition, $\lambda_0 = 2 d_0$ where d_0 is the period of the superlattice. Thus the thickness 't' of an individual layer is $t = \lambda_0/4$. Two filter thickness (93 Å and 122 Å) and crystal orientation (100) and (111) were investigated. The center stop band frequencies were 177 GHz and 225 GHz respectively. The experimental and theoretical results agreed well. A theoretical calculation showed very little change in the stop band with a 10 percent random thickness variation. To perform the experiment, superconducting tunnel junctions were used to generate and detect the phonons. The authors commented that without the development of the tunnel junction the experiment could not have been done.

In recent years these superlattice structures have been periodically doped with donor (n) and/or acceptor (p) impurities with insulating (i) material in between. Ruden and Dohler[4] did a theoretical study of acoustic phonons in n-i-p-i doped superlattices. They used a linear chain model and included the coulomb interaction. They concluded that the charge distribution did not remove the phonon degeneracy due to the folding back of the acoustic phonons. They also found that the folded back acoustic phonons were only slightly affected in the long wavelength limits. In this limit the high frequency acoustic phonons coincide with the optical phonons of long wavelength. This allows the longitudinal and transverse acoustic phonons to be excited by electromagnetic (e.m.) waves of long wavelength. Since the high frequency acoustic phonons can be excited by e.m. waves, Brillouin and Raman scattering is used to study these phonons. Quinn, Strom and Chang[5] used a Drude model approach to study the excitation of high frequency phonons in doped superlattices. This approach uses the electric field and charge distribution to predict the dispersion relation in the material. In the doped superlattice structure the charge distribution $\rho(z)$ is periodic with the layer spacing as the electric field

4. Ruden, P., and Dohler, G.H. (1983) Anisotropy effects and optical excitation of acoustic phonons in N-I-P-I doping superlattices, Solid State Comm., **45**(No. 1):23-25.

5. Quinn, J.J., Strom, U., and Chang, L.L. (1983) Direct electromagnetic generation of high frequency acoustic waves in semiconductor superlattices, Solid State Comm., **45**(No. 2):111-112.

E(z) slowly varies over the layer spacing. This means that E(z) and $\rho(z)$ will be peaked about the period "$q = n\pi/d$" where d is the thickness of a single superlattice layer and n is an integer. A resonance should occur for the frequency "$\omega = cq$" where c is the velocity of sound in the material. The resonance will generate high frequency acoustic phonons in the material. Both studies are in agreement and satisfy the Bragg condition. Ruden and Dohler[4] predicted coupling between the e.m. waves and the acoustic phonon modes for a AlGaAs/GaAs or InAs/GaSb superlattice of about 0.4 percent. The superlattice used in the model was 20-μm thick consisting of 2000 superlattice periods. This is on the same order as piezoelectric coupling in GaAs for an acoustic surface wave reported by Swierkowski et al.[6] Doping the superlattice does not appear to improve the acoustic phonon coupling of the AlGaAs/GaAs layers.

Since Narayanamurti showed that a superlattice could be used as an acoustic filter, this leads to using the filter as a resonator.[7] Using the concept of acoustic filter a stop band frequency is chosen. Once the stop band frequency is chosen, the period for the superlattice can be determined and an acoustic filter grown. The resonant cavity would then be grown on top of the acoustic filter. The acoustic filter would act as an acoustic energy barrier for the acoustic wave at the stop band frequency. The energy of the acoustic wave is then reflected back into a resonant cavity. The advantage of these resonators is the selection of the materials that can be used. By choosing them properly a temperature compensated resonator could be achieved.

3. PLASMONS

3.1 Surface Plasmons

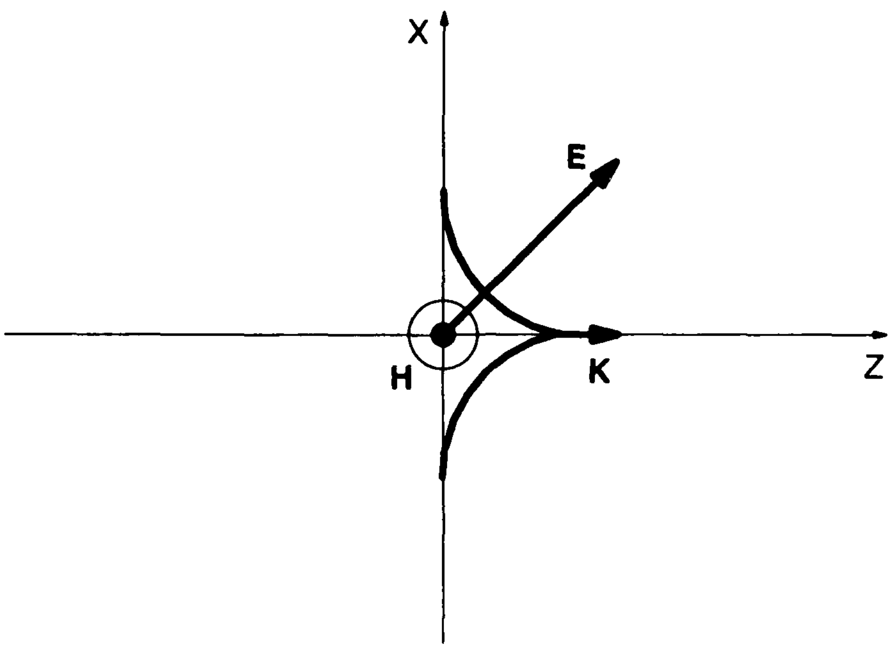
Let's first consider just the surface plasmon. In the metal, de-localized electrons form a plasma. This plasma exists throughout the metal and has a collective motion called a plasma oscillation.[8] The frequency of the plasma oscillation is $\omega_p = (4\pi ne^2/m)^{1/2}$ where n is the number of electrons, e is the electron charge and m is the electron mass. The plasma oscillation has

6. Swierkowski, S., Van Duzer, T., and Turner, C (1973) Amplification of acoustic surface waves in piezoelectric semiconductors, IEEE Trans. Sonics and Ultrasonics, SU-20(No. 3):260-267.

7. The concept of the resonator came from a private discussion among the author, Dr. Paul Carr, and Bruce Thaxter of RADC/EEAC.

8. Jackson, J. D. (1975) Classical Electrodynamics 2nd Ed., John Wiley & Son, Inc., New York, pp. 469-497.

associated with it a surface plasma oscillation[9, 10] located at the surface of the metal with a frequency of $\omega_p/\sqrt{2}$. Since the surface plasma oscillation (SPO) is the collective motion of charged particles, it has an electromagnetic field associated with it. This electromagnetic field is a transverse magnetic (TM) electromagnetic wave propagating along the metal surface. The wave is polarized with one electric field component perpendicular to the surface and the other tangent to the surface along the direction of propagation. Both components exponentially decay with distance from the surface as shown in Figure 2. This TM electromagnetic wave is called a surface plasma wave (SPW) and is localized at the surface.



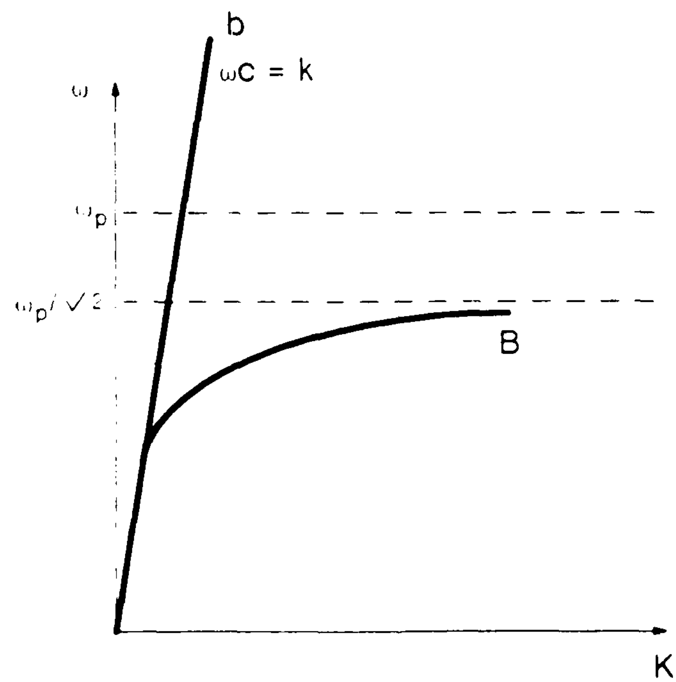
The surface plasma wave is a transverse magnetic (TM) electromagnetic wave. Here **K** is the wave vector and the direction of propagation of the wave. **E** is the resultant electric field vector which has a transverse component in the x-direction and a longitudinal component in the z-direction. **H** is the magnetic field vector which only has a transverse component in the y-direction coming out of the page. The exponential curves represent the decay of the wave into the dielectric metal.

Figure 2. Surface Plasmon Wave for a Dielectric-Metal Interface

9. Economou, E. N. (1969) Surface plasmons in thin films, Phys. Rev., **182**(No. 2):539-555.

10. Ritchie, R. H. (1957) Plasma losses by fast electrons in thin films Phys. Rev., **106**(No. 5):874-881.

There are two types of surface plasma oscillations, radiative and non-radiative. We shall discuss the non-radiative type alone. The SPW of the non-radiative SPO does not generally couple to free space electromagnetic waves. This is seen in the SPW dispersion relation for a dielectric-metal interface, represented by curve B in Figure 3. The light line for incident light, given by curve b, converges with the dispersion relation of the SPW (curve B) for long wavelengths, that is, as ω and $\underline{K}$ (wavevector) approach zero. Therefore, the SPW cannot couple to the incident light. A transverse magnetic (TM) surface electromagnetic wave (SEW) is employed to couple to the SPW.



CURVE b: Curve b is the dispersion relation for an electromagnetic wave in a vacuum and c is the velocity of light in a vacuum

CURVE B: Curve B is the surface plasmon dispersion relation where $\omega_p/\sqrt{2}$ is the surface plasmon frequency, and ω_p is the plasma frequency for the metal

Figure 3. Dispersion Relation for a Surface Plasmon Along a Dielectric-Metal Interface

A SEW on the surface of a dielectric material is analogous to a SPW on the surface of a metal in that their behavior is similar. A SEW (TM) was first coupled to a SPW on a smooth metal surface by Otto.[11] He used the method of attenuated total reflection.

Attenuated (or frustrated) total reflection is the attenuation of a reflected wave that has undergone total internal reflection. Total internal reflection[12] is the complete reflection of an electromagnetic wave incident on the interface of two media. Thus the intensity of the incident wave equals the intensity of the reflected wave $I_o = I_r$). The conditions for total reflection can be obtained from Snell's law $n_1 \sin \theta_i = n_2 \sin \theta_t$ where n_1 and n_2 are the indices of refraction of the media and θ_i and θ_t are the incident and transmitted angles respectively. Here one finds that if $\theta_t = 90°$ then $\sin \theta_i = n_2/n_1$. For $\sin \theta_i = n_2/n_1$ to have any physical meaning $\sin \theta_i$ must be less than one. Thus the index of refraction n_1 of medium 1 must be greater than the index of refraction n_2 medium 2 ($n_1 > n_2$). The angle of incidence at which total reflection occurs is $\theta_i = \sin^{-1}(n_1/n_2)$ and the angle is known as the critical angle. A diagram for total internal reflection is shown in Figure 4. When a transverse electromagnetic wave undergoes total reflection an SEW is produced at the interface of the two dielectric median. The attenuation of the totally reflected wave can be achieved by placing a poor dielectric (that is, a conductor) near surface that the SEW is propagating along. Otto's setup introduced a spacer dielectric (air) between the optical coupler (prism) and a metal film (silver) as shown in Figure 5.

In the experiment two conditions are necessary for coupling the SEW (TM) to the SPW. First, the optical coupler has to be placed close enough to the surface for the SEW (TM) and SPW to interact. Second, the phase velocities of the SEW (TM) and SPW must match, that is, energy and momentum must be conserved ($h\omega_{sew} = h\omega_{spw}$, $h\underline{K}_{sew} = h\underline{K}_{spw}$). With the introduction of the spacer dielectric these conditions can be satisfied. This is illustrated by curve A, the dispersion relation for the spacer-metal interface, and curve C, the light line for the SEW (TM) in Figure 6. Where the two lines intersect the phase velocities of the SEW (TM) and the SPW match. Energy can then be transferred from the SEW to the SPW of the metal.

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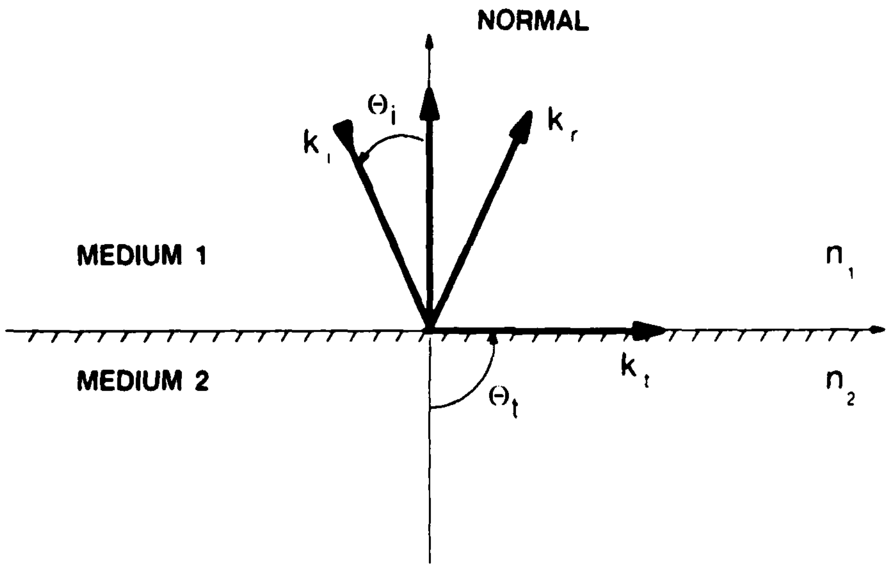
11. Otto, A. (1969) Excitation of nonradiative surface plasma waves in silver by the method of frustrated total reflection, Z. Physik, 216:389-410.

12. Halliday, D., and Resnik, R. (1967) Physics Parts I and II, John Wiley & Sons, Inc., New York, pp. 1024-1028.



The ray k_i is the incident wave and Θ_i is the angle of incidence which is equal to the critical angle. The ray k_t is the transmitted wave at an angle $\Theta_t = 90°$. The ray k_r is the *total reflected wave*. The necessary condition for total internal reflection is $n_1 > n_2$ where n_1 and n_2 are the indices of refraction for media 1 and 2 respectively

Figure 4. Total Internal Reflection

3.2 Surface Acoustic Plasmons

A similar situation arises in a doped superlattice structure. The charge impurities form what may be considered to be a two-dimensional electron gas in the superlattice. This allows the superlattice to be modeled as a two-dimensional plasma. Qin, Giuliani, and Quinn,[13] showed theoretically there is a surface acoustic plasmon associated with the surface plasmon in n-i-p-i doped superlattices. The surface acoustic plasmon is not a classical acoustic wave like a sound wave. It is called an acoustic plasmon because it has a linear dispersion relation ($\omega \propto k$) and is dependent on the charge density in the material. The surface acoustic plasmon's other characteristic is that the electrons and holes or ions lie in

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13. Qin, G., Giuliani, G.F., and Quinn, J.J. (1983) Acoustic surface plasmons in type-II semiconducting superlattices, Phys. Rev. B, 28(No. 10):6144-6146.

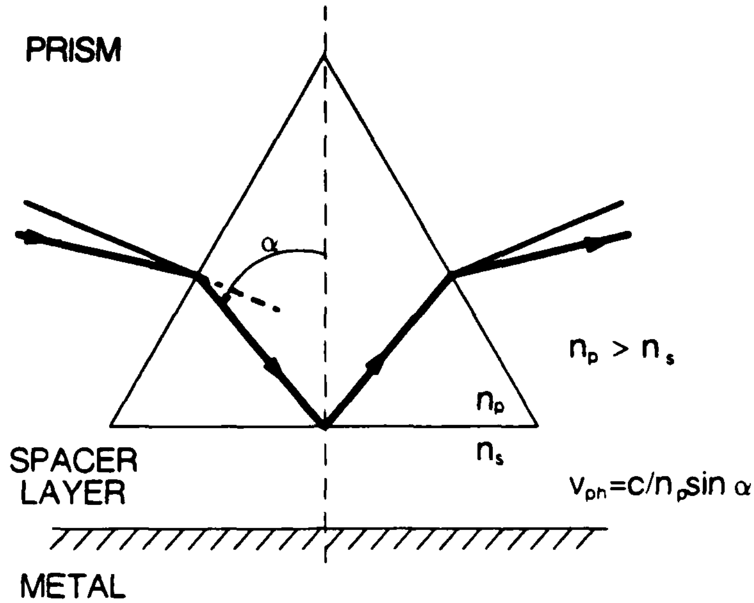
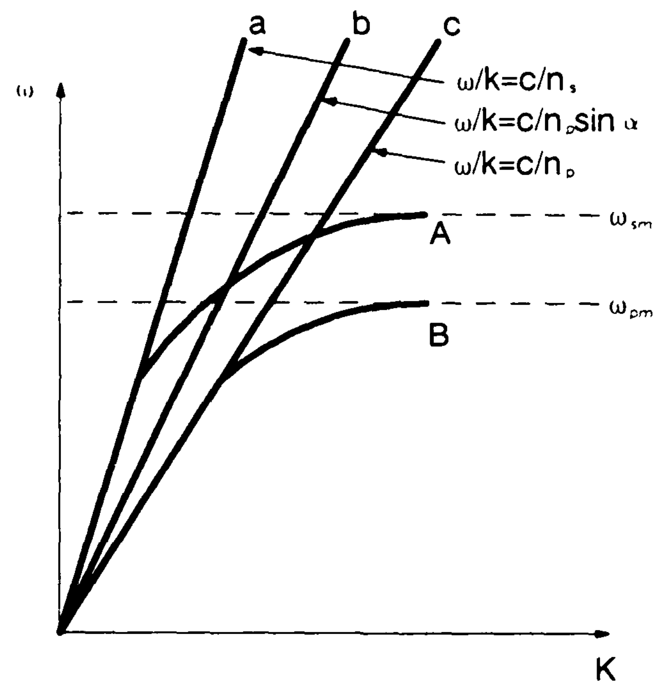


Figure 5 shows a dielectric-dielectric-metal configuration for exciting a surface plasmon. Here n_p and n_s are the indices of refraction for the prism and the spacer layer, respectively, where $n_p > n_s$ is the condition for total internal reflection. The phase velocity $v_{ph} = c/n_p \sin\alpha$ is velocity of a surface wave propagating along the prism-spacer layer interface, where α is the internal angle of incidence and c is the velocity of light in a vacuum.

Figure 5. Otto's Experimental Configuration

planes parallel to each other. Since the surface acoustic plasmon is associated with the surface plasmon, the surface plasmon can be used as a coupler for the surface acoustic plasmon. The space quantization of these ultra-thin layers yield other beneficial properties for these surface waves.

The surface waves are free from intrinsic Landau damping and their group velocities can be controlled through material processing. Landau damping does not occur because the two-dimensional boundary conditions for the surface plasmons and surface acoustic plasmons do not require that the energy and momentum of the wave vector be conserved, unlike the three-dimensional case. In the three-dimensional case where the energy and momentum of the wave vector must be conserved, the wave vector must decay into an electron and hole pair. The absence of Landau damping means that these excited surface modes will be



CURVE A: Curve A is dispersion of the non-radiated SPW at the spacer layer-metal interface and ω_{sm} is the surface plasmon *frequency for the spacer layer-metal* interface.

CURVE B: Curve B is the dispersion of the SPW if the prism and metal were in contact and ω_{pm} is the surface plasmon frequency for the prism-metal interface.

LINE a: Line a is the dispersion of the plane wave in the spacer layer.

LINE b: Line b is the dispersion of the plane wave in prism.

LINE c: Line c is the dispersion of the SEW along the prism-spacer layer interface. The intersection of line c with curve A is a resonance of the SPW with the SEW.

Figure 6. The Dispersion for a Plane Wave, SEW and SPW

long lived compared with a three-dimensional SPW. The propagation distance for a typical three-dimensional SPW is inversely proportional to the loss tangent of the material. The fact that these surface modes are long lived excitations makes them promising candidates for surface wave devices.

Three components come immediately to mind for applying surface plasmons or surface acoustic plasmons: a transducer, a delay line, and a mixer. These components are all electro-optical components. The first, the transducer, has already been shown to be feasible using surface plasmons on silicon by Derov, Teng and Karakashian.[14] It is a simple two terminal component consisting of a prism coupler and a Schottky diode. Three things will affect the frequency response of this component: the diffusion of carriers through the material, the drift time of the carriers in the depletion region and the capacitance of the diode junction. The effect of the diffusion carriers and the drift time in the depletion region is optimized by using a Schottky diode since the junction is formed at the surface of the diode. The capacitance C of the diode junction along with the load resistance R yields an RC time constant. The RC time constant would then determine the frequency response of the component. Though the surface plasmon is excited by an optical signal, the optical signal can be modulated at microwave and millimeter wave frequency. The second component, a delay line, would provide a delay in the time domain. Since the group velocity of the surface acoustic plasmons can be controlled in the material growth process, this adds another parameter that can be used in designing the delay line. Active devices such as diodes and FETs could be placed along the propagation path to act as taps for a variable delay line. Delays on the order of nanoseconds should be achievable since a typical phase velocity for a surface acoustic plasmon is on the order of 10^7 cm/sec. The third component is a diode mixer. The diode mixer would be a three-terminal component where the rf signal is input as an optically modulated signal and the local oscillator would be input to the diode in the normal way. The output would then go to a filter network to eliminate any harmonics from the intermediate frequency.

3.3 Surface Magnetoplasmon Isolator

A magnetoplasmon resonance is the result of placing a material with a plasmon resonance in a magnetic field. A magnetoplasmon is the interaction of a cyclotron resonance and a plasmon resonance in the material. Since the magnetoplasmon is the interaction of the cyclotron and plasmon resonance, a cyclotron orbit must occur. For a cyclotron orbit to occur its radius must be less than the mean free path for an electron in the material. If the radius of the cyclotron orbit is greater than the mean free path of the electron, the electron will collide with the lattice or an impurity in the crystal and the energy and the momentum of the electron will be lost to the lattice or impurity. Thus a magnetoplasmon oscillation will not occur.

14. Derov, J., Teng, Y.Y., and Karakashian, A.S. (1983) Angular scan spectrum of surface plasma excitation on a Schottky diode, Phys. Lett., 95A(No. 3, 4):197-200.

Brion et al[15] showed theoretically that the surface magnetoplasmon, associated with the magnetoplasmon oscillation, was a nonreciprocal phenomena. Bolle and Talisa[16] showed theoretically that the nonreciprocal effects of the surface magnetoplasmon make a 500-GHz isolator on GaAs feasible. The isolator proposed by Bolle and Talisa requires an operating temperature of 77 K. This increases the mean free path of the electron in the GaAs and allows the isolator to operate at 500 GHz. Since the mean free path for an electron in a two-dimensional electron gas of a semiconductor superlattice is greater than that of GaAs. it may be more practical to use a superlattice to make the isolator. In fact if the mean free path in the superlattice is large enough the isolator may operate at room temperature.

4. CONCLUSION

We want to look at the potential applications for these materials. The acoustic phonon, surface plasmon and surface acoustic plasmon phenomena show promise for applications in the millimeter wave and possibly the microwave region of the spectrum. The dielectric phonon filter and resonator, through the use of Molecular Beam Epitaxy, shows promise for wafer level integration. The other phenomena, surface acoustic plasmons and surface plasmons show promise for microwave and millimeter wave applications. The transducer could be important in the optical coupling of T/R modules with phased arrays. The surface acoustic plasmon may have applications as a delay line since the group velocity of the surface wave can be controlled in the processing of the material. Other interesting applications like the diode mixer may come about by the experimental investigation of the surface plasmon and surface acoustic plasmon phenomena. With the use of superlattice materials the surface magnetoplasmon isolator may operate at room temperature and become more practical for wafer level integration.

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15. Brion, J. J., Wallis, R. F., Hartstein, A., and Burstein, E. (1972) Theory of surface magnetoplasmons in semiconductors, Phys. Rev. Lett., 28(No. 22):1455-1458.

16. Bolle, D. M., and Talisa, S. H. (1981) Fundamental considerations in millimeter and near-millimeter component design employing magnetoplasmons, IEEE Trans. MTT, MTT-29(No. 9):916-922.

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6. Swierkowski, S., Van Duzer, T., and Turner, C. (1973) Amplification of acoustic surface waves in piezoelectric semiconductors, IEEE Trans. Sonics and Ultrasonics, SU-20(No. 3):260-267.
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