AN ELECTRONICALLY VARIABLE SURFACE ACOUSTIC WAVE PHASE SHIFTER

by

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A surface acoustic wave phase shifter has been realized by utilizing the interaction between the piezoelectric fields of a surface wave and an adjacent semiconductor. One important feature of this interaction is that the velocity of the surface wave depends on the electrical properties of materials placed in the vicinity of, but not mechanically touching, the piezoelectric. For example, Campbell and Jones[1] have calculated the velocity of surface waves on the y-plane of $LiNbO_3$ for the case of a free surface (Fig. 1, $\omega h = \infty$) and the case where an infinitesimally thin perfect conductor is placed on the surface ($\omega h = 0$). For waves propagating in the Z-direction ($\theta = 90^o$) the velocity decreases by about 2.5% when an electrical short is placed at the surface. This velocity change can be achieved by purely electrical means by varying the free carrier concentration at the semiconductor surface. The method we have used to accomplish this is to apply an electric field normal to the semiconductor surface as illustrated in the inset to Fig. 2. Here the semiconductor functions as one plate of a capacitor and the induced charge at the surface then varies with the applied voltage V.

Figure 3 is a photograph looking through a $LiNbO_3$ delay line at a rectangular wafer of silicon. The darker areas on either side of the lighter shaded channel down the center of the silicon are sputter deposited films of SiO_2 of about 500 Å thickness and function as spacers. The acoustic beam propagates along this channel between interdigital transducers which are visible toward both ends of the crystal.

Experiments were performed using a wafer of 30,000 ohm-cm n-type silicon pressed onto the spacer rails of a Y-Z $LiNbO_3$ delay line. The silicon surface is given an 1100°C dry oxidation to reduce fast surface states which act as trapping centers. However, the oxidation introduces fixed positive charges into the oxide which induce a layer of free electrons (accumulation layer) even in the absence of an applied voltage.

Figure 2 contains experimental results at 170MHz. The acoustic wavelength at this frequency is about 20 microns. The portion of the silicon sample close enough to the $LiNbO_3$ surface to interact with the surface wave was about 8mm or 400 wavelengths. Thus, even though the fractional velocity change was less than one per cent, overall phase shifts of more than 4π radians were observed. In order to vary the surface carrier concentration to the degree required for this experiment electric fields of the order of 10^4V/cm must be applied to the silicon surface. Such fields can be readily attained with a few hundred volts bias by virtue of the high dielectric constant ($\varepsilon_{yy}/\varepsilon_0 = 84$) of the $LiNbO_3$ in the Y-direction.

The basic features of the data can be understood as follows: For large negative voltages on the silicon the electron density in the accumulation layer increases and tends to behave as a short circuit to the surface wave. The phase shift at this point is at a maximum (i.e. the surface wave velocity is at a minimum), and the attenuation due to the carriers is at a minimum. The sheet electron density at this point is estimated to be around $2 \times 10^{11} cm^{-2}$. For positive voltages the electron concentration diminishes and the surface wave velocity increases until the flat band condition is reached. This represents the point at which essentially no free charge is present in the semiconductor, and it occurs when the applied voltage just offsets the field created by the fixed positive oxide charge. The surface wave attenuation at this point is also at a minimum. With a further increase in voltage the surface becomes p-type (i.e. free holes appear at the surface) and the phase shift and attenuation again vary in a manner similar to the case of the n-type surface.

Shown for comparison with the data points are theoretical curves based on the work of Ingebrigtsen[2] and Kino and Reeder[3] for the case of a sheet of carriers much thinner than a wavelength. The change in the propagation constant $\Delta\beta = \Delta\beta_r + j\Delta\beta_i$ is found from the following expressions:

$$\Delta\beta_i = \frac{-K^2}{2}\beta_a \frac{x}{1+x^2}$$

$$\Delta\beta_r = \frac{K^2}{2}\beta_a \frac{x^2}{1+x^2}$$

where K^2 is an effective electromechanical coupling constant, $x = Rn_s e\mu_s/\epsilon v_a$, R is a geometrical factor of the order of 1, $\beta_a=\omega/v_a$, v_a is the surface wave velocity, and n_s and μ_s are the carrier concentration per unit surface area and the surface mobility. Carrier diffusion has been neglected and should not be important at these frequencies.

The surface carrier density n_s is proportional to $|V-V_o|$ where V_o=515 volts is the flat band voltage. The surface mobility is assumed to constant, and the ratio of electron to hole mobilities was taken to be 2.9. These latter two assumptions are probably somewhat in error, but a more careful treatment of this point should not change the curves drastically. The theory has been fitted to the phase shift data, using a value of K^2 in rough agreement with a calculated value. The predicted attenuation, however, is much greater than observed. Capacitance-voltage measurements on the oxide have shown that the distribution of positive charge is highly non-uniform. Approximately 3mm of the sample had oxide charge of about 10^{11}cm^{-2} while the density in the remainder of the sample was higher. The oxide charge calculated from the flat-band voltage V_o of the phase-attenuation data is 8×10^{10}cm^{-2}, in reasonable agreement with MOS measurements. In view of the gross inhomogeneities in the oxide charge a meaningful comparison of experiment and theory is not possible.

At the strong accumulation and flat band points the attenuation due to the silicon was 7dB for a phase shift of 750 degrees. This means less than 3.5 dB per 2π radians of phase shift when the device is switched between these two points. The voltage change needed to operate the device in this way is about 900 volts. However, the thickness of the $LiNbO_3$ crystal is the principal factor in determining this voltage and in these experiments was 2.5mm. Using a much thinner crystal would result in a phase shifter operating at substantially reduced voltages.

Acknowledgement

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References

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2. K.A. Ingebrigsten, J. Appl. Physics. 41, p.454, (1970).
3. G.S. Kino and T.M. Reeder, Microwave Laboratory Report 1842, Stanford University, Stanford, California, July 1970.

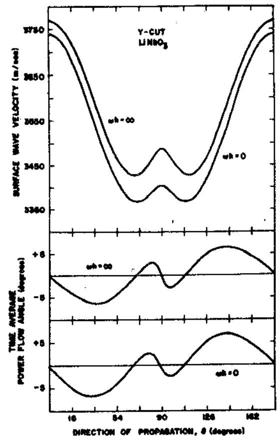

Figure 1. Calculated surface wave velocity on Y-cut $LiNbO_3$ for the case of a free surface (ωh=∞) and for a surface coated with an infinitesimally thin perfect conductor (ωh = 0). Reprinted from Microwave Acoustics Handbook, Vol. 1, Surface Wave Velocities by A.J. Slobodnik Jr. and E.B. Conway.

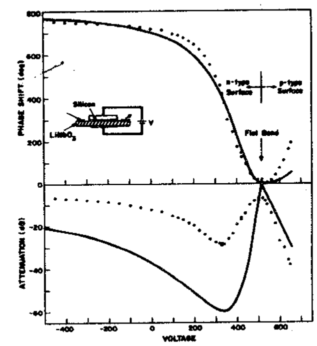

Figure 2. Experimental data on phase and attenuation of 170MHz surface waves as a function of bias applied between the silicon and a conducting plate under the delay line. Solid curve is a theoretical calculation.

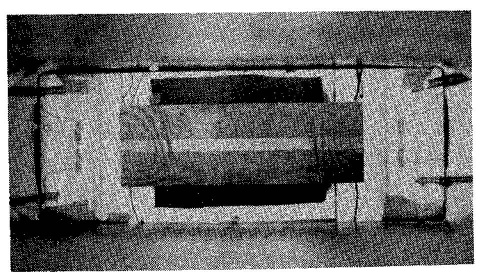

Figure 3. Photograph of the device looking through the $LiNbO_3$ crystal at the silicon wafer pressed down on the opposite surface. The small bubbles are embedded in a transparent cement which is used to mount the $LiNbO_3$ on a glass base plate.