EFFICIENT THIN FILM $InSb/LiNbO_3$ CONVOLVER

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Summary

A thin film $InSb/LiNbO_3$ acoustoelectric convolver has been successfully fabricated and operated at a center frequency of 100 MHz. The InSb is first deposited and then etched to the waveguide with the width of 1 mm. The Hall mobility and σh of the InSb with a thickness of about 500 Å are μ_H=1041 $cm^2/V \cdot sec$ and σh=34.3 μS, respectively. A convolution efficiency of -59 dBm was obtained experimentally.

1. Introduction

There are various types of convolvers in combination of semi-conducting and piezoelectric materials[(1)—(3)]. The successful use of a gap-coupled $InSb/LiNbO_3$ convolver has been reported by Leonberger, etc[(4)]. The monolithic type of convolvers, which are composed of different semiconducting and piezoelectric materials and combined acoustically, have several merits, such as high efficiency due to the high coupling, uniform interaction over a long delay time and applicability for high frequencies, etc. However, there remain some difficulties in making a semiconducting thin film having excellent electrical characteristics. For these reasons, we have tried several methods of making InSb thin film and were able to obtain the good properties of film with convolution efficiency of -59 dBm.

2. Theoretical Analysis and Numerical Results

The theoretical analysis of nonlinear interactions arising from space charge nonlinearity in a separated-media coupled semiconductor/piezoelectric system have been reported by G.S. Kino et al[(5)] and O.W. Otto[(6)]. G.S. Kino et al analysed the convolver by regarding the semiconductor as a distributed varactor. O.W. Otto assumed the nonlinear mechanism to be exclusively the space charge nonlinearity in the semiconductor arising from the nonlinear current density. We now analyse the monolithic convolver such as $InSb/LiNbO_3$[(7)] and plate convolver[(8)], in accordance with the space charge nonlinearity model. In this analysis of a monolithic convolver the following assumptions are made:

(1) The overcoating film thickness is very thin and therefore films have no affect on the propagational characteristics of acoustic surface waves.
(2) Dispersion properties of acoustic surface waves are neglected.
(3) Small signal analysis are applied.
(4) The material constants are nondispersive.

Figure 1 shows the configuration of the monolithic convolver and co-ordinate system, where d and ℓ are the thickness of dielectric thin film 1 and 2, h is the thickness of the semiconductor film, x is the propagation direction of the surface wave and y is the normal to the surface.

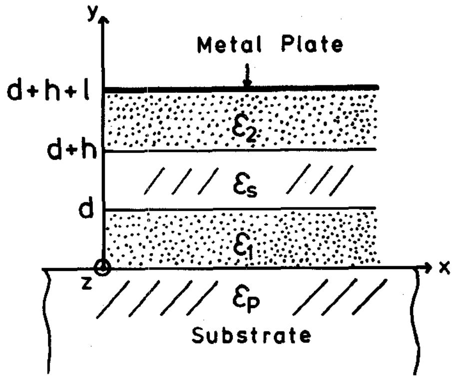


Figure 1 Configuration and Co-ordinate System.

Poisson's equation, the equation of motion and the equation of current density with constitutive relations are given as follows:

$$\varepsilon \nabla \cdot \mathbf{E} = \rho \quad (1), \qquad \rho' \frac{\partial^2 \mathbf{u}}{\partial t} = \nabla \cdot \mathbf{T} \quad (2)$$

$$\nabla \cdot \mathbf{J} = -\frac{\partial \rho}{\partial t} \quad (3), \qquad \mathbf{D} = \boldsymbol{\varepsilon}^T \cdot \mathbf{E} + \mathbf{d} : \mathbf{T}, \quad (4)$$

where $\mathbf{J}$ is carrier current density, $\mathbf{E}$ is electric field, and ρ is the perturbation in charge density relative to equilibrium value ρ_0, ρ' is the mass density, $\mathbf{D}$ is electric displacement, $\mathbf{u}$ is the displacement, and $\mathbf{T}$ is the acoustic stress tensor. The material constants σ, ε, μ, D, $\mathbf{d}$ and $\boldsymbol{\varepsilon}^T$ are conductivity, permittivity, mobility, diffusivity, the piezoelectric tensor and permittivity at constant stress, respectively. All nonlinear phenomena arise from the nonlinear current density

$$\mathbf{J}_n = \mu \rho \mathbf{E} \quad (5)$$

Combining Eqs.(1)~(5) and applying the boundary conditions at $y=0$, $y=d$, $y=d+h$, and $y=d+h+\ell$, the convolution voltage V_n (for $\beta=0$, β: wave number) is given by integral of the electric field of y-component from $y=d$ to $y=d+h$

$$V_n = -\int_d^{d+h} E_{y2\omega,0}\,dy = -\frac{1}{D\varepsilon_p} \sum_p \frac{J_{py}}{K_p(K_p^2-K_0^2)} \cdot S_p \quad (6)$$

where K_p's are wave number, J_{py}'s are nonlinear currents corresponding to K_p's, $K_0 = \sigma(1+\eta)/D\varepsilon_s$, $\eta = i\omega/\omega_c$, $\omega_c = \sigma/\varepsilon_s$ and

$$S_p = (1-e^{-K_p h})\left(1 - \frac{K_p}{K_0} \cdot \frac{\tanh(\frac{1}{2}K_0 h)}{\tanh(\frac{1}{2}K_p h)}\right) \quad (7)$$

The relation between the acoustic power P(W/m) and potential ϕ_a are given as follows

$$\phi_a^2 = \frac{4}{\omega(\varepsilon_0+\varepsilon_p)} \cdot \frac{K^2}{2} \sqrt{P_{a_1} P_{a_2}} \; . \; . \; . \; . \; . \quad (8)$$

where K^2 is effective electromechanical coupling coefficient and ϕ_a is the potential at $y=0$.

The M value (the efficiency) of the convolver:

$$M = \frac{V_{rm}}{\sqrt{P_{a_1} P_{a_2}}} = \left| \frac{\mu}{D} (K^2 - \beta^2) \frac{2}{\omega(\varepsilon_p + \varepsilon_0)} \cdot K^2 (1+N)^2 e^{-2\beta d} \sum_p \frac{T_p}{K_p (K_p^2 - K_0^2)} \cdot S_p \right| \quad (9)$$

where V_{rm} is the rms open-circuit voltage, $N = (\varepsilon_p + \varepsilon_1 \tanh\beta\ell)/(\varepsilon_1 + \varepsilon_p \tanh\beta d)$ and T_p is determined by the boundary conditions.

In Figs. 2 and 3, the magnitude of M is plotted for various ranges of frequency, conductivity and mobility for the structure of InSb/128° rotated Y-cut, X-propagating $LiNbO_3$. The material parameters used are $\varepsilon_p/\varepsilon_0 = 65.1$, $\varepsilon_s/\varepsilon_0 = 16.0$, $\varepsilon_1/\varepsilon_0 = \varepsilon_2/\varepsilon_0 = 5.0$, $v = 4000$ m/s, $K^2 = 0.055$, operating temperature of 300°K. Figure 2 shows the convolver M value vs. input frequency, f with conductivity, σ as a parameter for a InSb/$LiNbO_3$ system. As InSb film has a relatively high conductivity, the convolver works best at high frequencies.
Fig. 3 shows the M value vs. input frequency, f with mobility, μ as a parameter for InSb/$LiNbO_3$ systems.

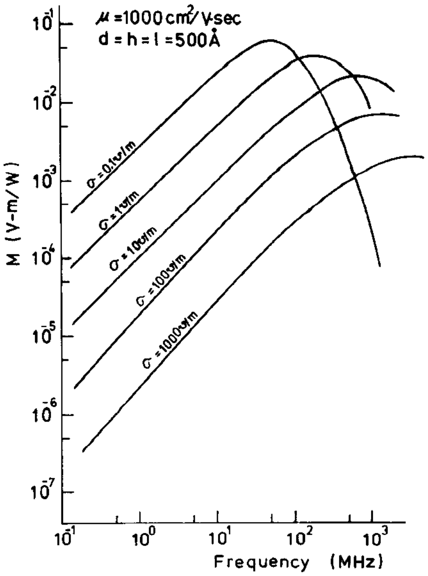


Figure 2

Convolver M value vs. input frequency, f with conductivity, σ, as a parameter for thin film InSb/$LiNbO_3$ convolver.

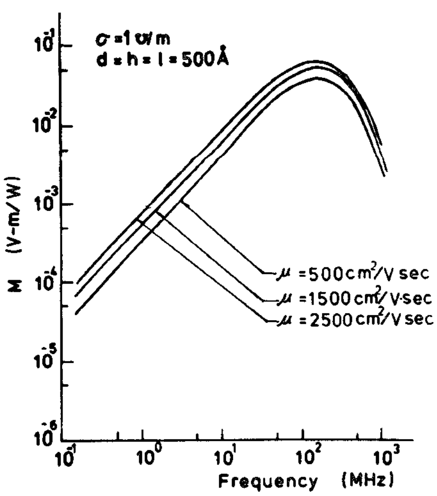


Figure 3

M value vs. f with mobility, μ, as a parameter.

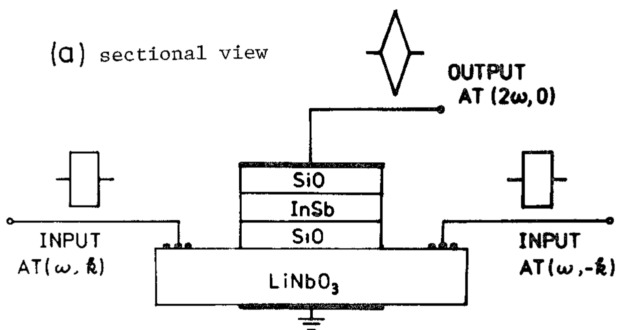
3. Experimental results and Discussion

First SiO film was evaporated about 500 Å on 128° rotated Y-cut X-propagating $LiNbO_3$. Then InSb film was prepared by the resistive heating method[9] under the following conditions: (1) the mobility and carrier density of the source InSb bulk were 4.4~5.5 × 10^5 cm²/V · sec and 1~2 × 10^{14}/cm³ at 77° K, respectively; (2) the substrate temperature was maintained constant at 270° C through the entire period of deposition and raised to 350°C after evaporation; (3) the evaporation temperature varied from 950° C to 1040° C for 14 sec.
By overcoating the SiO thin film at substrate temperature of about 95° C, the electrical properties of InSb were improved, especially in mobility. The Hall mobility and σh used in convolvers were 1041 cm²/V · sec and 34.3 μS at thickness h=500 Å, respectively. Figure 4 shows the structure of the convolvers. Input and output interdigital electrodes are as follows: finger pairs N=27, apertures W=1.5 mm, propagation distance ℓ=9 mm.

Monolithic InSb/$LiNbO_3$ convolvers had first been constructed and measured for the longitudinal modes[7]. In this paper, the acoustoelectric measurements are made for the transverse modes.

The convolution efficiency F and insertion loss L were measured with 100 MHz acoustic surface waves. Here, $F = 10 \cdot \log(\frac{P_3}{P_1 P_2})$ where P_3 is the convolution output signal power and P_1 and P_2 are the signal power applied to the two input transducers. Also, $L = 10 \cdot \log(\frac{P_1}{P_{20}})$ where P_1 is the power applied to one transducer and P_{20} is the amount of that power extracted from the other transducer after the wave has transversed the length of the InSb/$LiNbO_3$ structure. The insertion loss L is the -8 dB of bare $LiNbO_3$ delay line and -16 dB of convolvers with InSb thin films.

By measuring the circuit parameters of the measurement circuit and relation between the input voltage and acoustic power, rms open-circuit voltage V_{rm} is calculated. The experimental value of M is determined from these values. Also, theoretical value of M is calculated by using eq.(9).



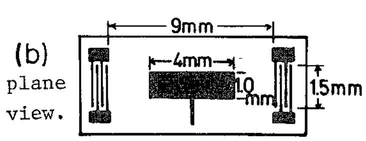


Figure 4

Configuration of thin film InSb/$LiNbO_3$ convolver

Figure 5 shows the insertion loss L and conversion efficiency F versus the input frequency. The variation of F is the same as that of L. So, we are able to get the device with the wide bandwidth by using the wide bandwidth transducers.

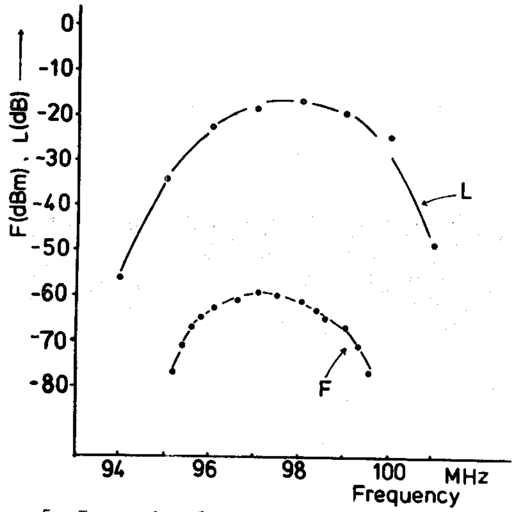


Figure 5 Insertion loss L and convolution efficiency F vs. f, pulse duration of 0.8μS, input Power $P_1 = P_2 = 25$ dBm.

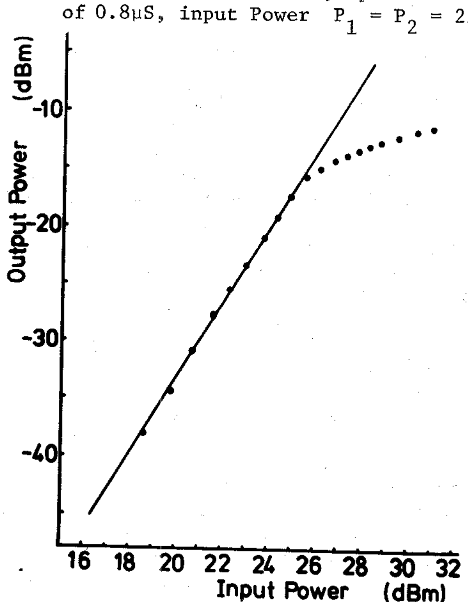


Figure 6 Output convolution power vs. input power.

Figure 6 shows the bilinearity and saturation characteristics of the device. An output dynamic range of 40 dB was observed and good bilinearity was achieved.

Figure 7 shows oscillogram of typical convolution output at the input power of 25 dBm. The photograph shows the convolution signal for equal amplitude 0.8 μS surface wave pulses. The -59 dBm efficiency shown is somewhat higher than that of other types of convolvers, such as, gap coupled Si and InSb/$LiNbO_3$ convolvers, ZnO/Si convolver and plate convolver.

The experimental value of M is $M_{ex} = 2.4 \times 10^{-4}$ V·m/W and theoretical one is $M_{th} = 2.3 \times 10^{-4}$ V·m/W. We can say that the M_{ex} fairly agrees with the M_{th}.

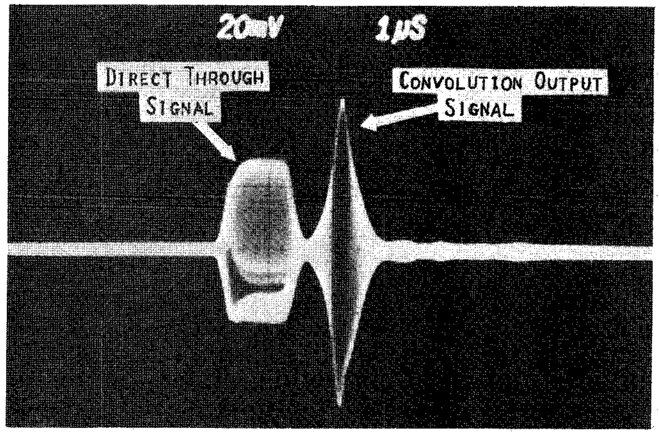


Figure 7 Convolution output for 0.8μS equal amplitude pulse for thin film InSb/$LiNbO_3$ convolver at 100 MH_z.

4. Conclusion

We have constructed an efficient thin film InSb/$LiNbO_3$ convolver. Moreover, we expect to be able to obtain more efficient convolvers in the future, as we can fabricate the better properties of InSb thin films on $LiNbO_3$. A device with wideband, uniform interaction, high frequency and long time delay is presently under investigation. The monolithic device configuration becomes increasingly attractive for signal-processing application and should be a viable competitor to an airgap configuration.

References

(1) O.W. Otto and N.J. Moll, "Lithium-Niobate-Silicon surface wave convoluter", Electron. Lett., Vol.8, No.24, Nov. 1972, pp.600-602.

(2) B.T. Khuri-Yakub and G.S. Kino, "Monolithic waveguide Zinc-Oxide-on-Silicon convolver", Electron. Lett., Vol.12, May 1976, pp.271-272.

(3) J.H. Cafarella, J.A. Alusow, W.M. Brown and E. Stern, "Programmable matched filtering with acoustoelectric convolvers in spread-spectrum systems", 1975 Ultrasonic Symposium, IEEE Cat. #75 CHO 994-4SU, Sept. 1975, pp.205-208.

(4) F.J. Leonberger, R.W. Ralston and S.A. Reible, "Gap-coupled InSb/$LiNbO_3$ acoustoelectric convolver operating at 77 °K", Appl. Phys. Lett., 33(6), 15 Sept. 1978, pp.484-486.

(5) G.S. Kino and H. Gautier, "Convolution and parametric interaction with semiconductors", J. Appl. Phys., Vol.44, No.12, Dec. 1973, pp.5219-5221.

(6) O.W. Otto, "Theory for nonlinear coupling between a piezoelectric surface and an adjacent semiconductor", J. Appl. Phys., Vol.45, No.10, Oct. 1974, pp.4373-4383.

(7) K. Yamanouchi, T. Aida and K. Shibayama, "Nonlinear Coupling between a piezoelectric surface and semiconducting thin film", Reports of the 1975 Autumn Meeting Acoust. Society of Japan 3-2-3, Oct. 1975, pp.459-460 (in Japanese).

(8) P. Defranould and C. Maerfeld, "A SAW planar piezoelectric convolver", Proc. IEEE, Vol.64, No.5, May 1976, pp.748-751, and R.D. Colvin and P.H. Carr "Surface-acoustic-wave plate convolvers at $1GH_z$",Appl. Phys. Lett., 35(7) 1 Oct. 1979, pp.522-523.

(9) K. Yamanouchi, T. Konno and K. Shibayama, "Effect of overcoating SiO thin films on monolithic elastic surface-wave amplifiers", Proc. of IEEE, Vol.13, No.4, April 1975, pp.726-727.