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Basic Characteristics of Surface-Acoustic-Wave Convolver in Monolithic MIS Structure

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I. Introduction Recently, interesting works[1,2] have been published on the gate-voltage dependence of surface-acoustic-wave (SAW) convolution in the monolithic MIS structure such as $Si/SiO_2/ZnO$/Metal system. However, the theoretical analysis of the experimental data could not be carried out because there is no theory[3] for the gate-voltage dependence of SAW convolution. In this paper, we propose a new nonlinear theory including the gate-voltage dependence and the effect of surface states based on a simple model of the monolithic system, and then we confirm our theory in the experiment on a $Si/SiO_2/ZnO/M$ system.

II. Theory In Fig.1 is shown a convolver configuration of n-$Si/SiO_2/ZnO/Al$ system, on which we develop the theory. We make the following assumptions. i) One-dimensional model ; we treat the interaction only in the x direction. This assumption is valid when $W \ll \lambda$ (W: width of depletion layer, λ: wavelength of SAW). ii) Quasi-static condition; it is sufficient to solve only Poisson's equation under the quasi-static condition when $\omega_c \gg \omega$ (ω_c: dielectric relaxation frequency, ω : angular frequency of SAW). This assumption means that we consider the lossless medium. iii) Constant transverse field approximation in ZnO; the electric field induced by SAW is transverse to the propagation direction and is constant within ZnO. This assumption is valid when $d \ll \lambda$ (d: width of ZnO). The above assumptions are valid for the usual system of n-Si (ρ=100Ωcm, μ=1500cm^2/V·s, T=300K) when f$\lesssim$100 MHz.

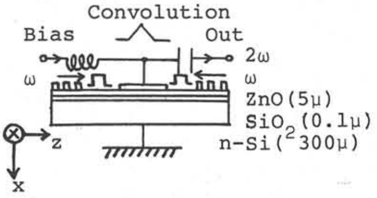

Fig. 1

When we take out the convolution output using the parallel peaking circuit, the equivalent circuit of our system is given as shown in Fig.2.

We can develop the theory by extending the usual C-V analysis of MIS structure[4] to include the nonlinear terms. If we denote the potential in the semiconductor by

$$\psi_s = \psi_{s0} + \delta\psi_s \text{ -----(1)} \quad (e\delta\psi_s/kT < 1)$$

(ψ_{s0}: dc gate potential, $\delta\psi_s$: induced ac gate potential), the final expression of the current is given by

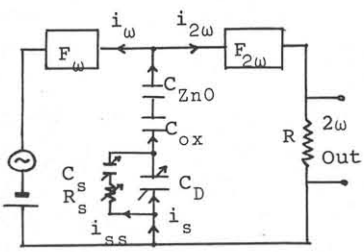

Fig. 2

$$i_T = i_{s,\omega} + i_{s,2\omega} + i_{ss,\omega} + i_{ss,2\omega} \text{ -----(2)}$$

where $i_{s,\omega} = i\omega C_{D,\omega}\,\delta\psi_s$ ---(3), $\left[C_{D,\omega} \equiv (\partial Q_s/\partial\psi_s)_{\psi_{s0}}\right]$,

$$i_{s,2\omega} = \frac{1}{2}(i2\omega C_{D,2\omega})\,\delta\psi_s^2 \text{ ----(4)}, \quad \left[C_{D,2\omega} \equiv (\partial^2 Q_s/\partial\psi_s^2)_{\psi_{s0}}\right],$$

$$i_{ss,\omega} = \left\{\frac{e^2 N_{ss}}{kT}\cdot\frac{i\omega f_0(1-f_0)}{(1+i\omega f_0/c_n n_{s0})}\right\}\delta\psi_s \text{ ---(5)}, \quad i_{ss,2\omega} = \frac{1}{2}\left\{\frac{e^3 N_{ss}}{(kT)^2}\cdot\frac{i2\omega f_0(1-f_0)(1-2f_0+i\omega f_0/c_n n_{s0})}{(1+i2\omega f_0/c_n n_{s0})(1+i\omega f_0/c_n n_{s0})}\right\}\delta\psi_s^2 \text{ ....(6)}$$

(Q_s: space charge at the surface of semiconductor, N_{ss}: surface state density, c_n: capture cross section of electrons, f_0: Fermi distribution at $\psi_s=\psi_{s0}$, n_{s0}:surface electron concentration when the Fermi level lies on the surface level).

The relation between the total potential δV in Fig.2 and $\delta\psi_s$ is given by

$$\delta\psi_s = \delta V/(1 + C_{D,\omega}/C_i) \text{ -------(7)}.$$

In the case of ideal MIS structure, we obtain

$$i_{s,2\omega} = (1/2)\{i\,2\omega\,(\partial C/\partial V)_{V_0}\}\,(\delta V)^2,\ \left[(\partial C/\partial V)_{V_0} = (\partial C_{D\omega}/\partial \psi_s)_{\psi_{s0}} / ((C_{D\omega}/C_i)+1)^3,\ \frac{1}{C} = \frac{1}{C_i} + \frac{1}{C_{D\omega}}\right] \cdots (8)$$

which gives the peak at

$$\psi_{s,peak} = -(1/2\beta)(1 + C_i/C_{D,FB}) \cong -1/2\beta \ \text{-------}(9),$$

where $C_i \ll C_{D,FB}$ ($C_{D,FB}$: depletion layer capacitance at the flat band, $1/C_i = 1/C_{ZnO} + 1/C_{ox}$). Therefore, the convolution signal (8) in the ideal MIS structure is proportional to the derivative of C-V curve and has the peak at $\psi_{so} = -1/2\beta = -e/2kT = -0.013V$, i.e., near the flat band.

III. Experiment We have carried out the experiment by using the system shown in Fig.1. The capacitance C_ω(f=50 kHz) and the SAW convolution signal (2f=100 MHz) are shown in Fig.3. The curves of $C_{2\omega}$-V and $G_{2\omega}$-V (G: conductance) are shown in Figs.4 and 5 and correspond to the imaginary and real part of 2ω current component, respectively. Since $G_{2\omega}$ is smaller than $C_{2\omega}$ in our sample, the 2ω component of the current responsible for the convolution is determined by $C_{2\omega}$ component. As is clearly seen in Figs.3 and 4, the gate-voltage dependence of the convolution is very similar to that of $C_{2\omega}$ in agreement with our theory. The shift of the peak in the two curves is caused by the different response of surface states at the two frequencies, 100 kHz and 100 MHz.

VI. Conclusion (1) We have shown that the convolution signal corresponds to the derivative of C-V curve in the ideal MIS structure and the effect of surface states appears in the peak shift. (2) We have shown a guiding principle that we should improve the convolver efficiency based on a concept of loss-less parametric operation of variable capacitance.[5] Based on this guiding principle we are trying to improve the convolver efficiency and the results will be presented at the Conf..

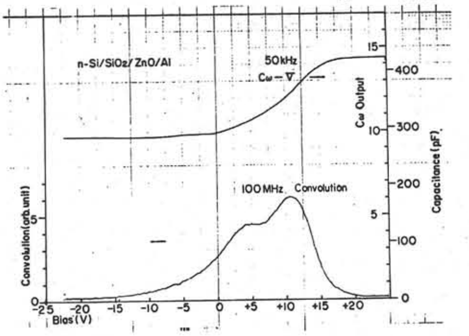

Fig. 3

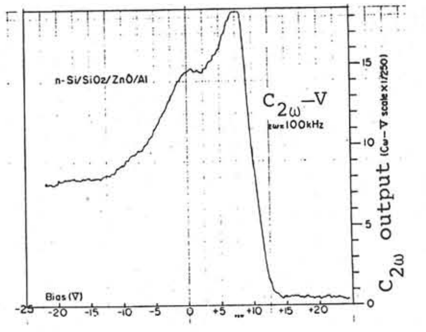

Fig. 4

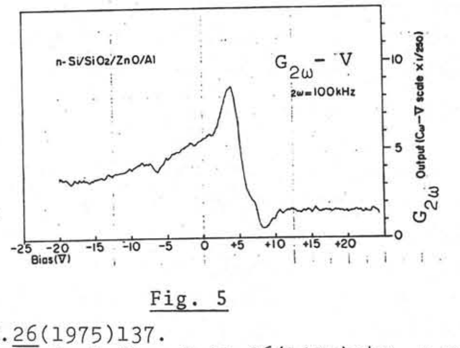

Fig. 5

References

1) L.A.Coldren:Appl.Phys.Lett.25(1974)473; ibid.26(1975)137.
2) L.A.Coldren:Appl.Phys.Lett.27(1975)6; K.L.Davis:Appl.Phys.Lett.26(1975)143; J.K. Elliott, R.L.Gunshor, R.F.Pierret and D.K.Davis:Appl.Phys.Lett.27(1975)179.
3) G.S.Kino and H.Gautier (J. appl. Phys. 44 (1973) 5219) have developed a theory based on the "varactor model" under flat band and open circuit conditions. H. Hayakawa and K. Hoh (Private communication) have tried to extend Kino-Gautier's theory to discuss the gate-voltage dependence under the open circuit condition. However, our experiments have been carried out so far under the short circuit condition.
4) H. Nicollian and A. Goetzberger:Bell Syst. tech. J. 46(1967)1055.
5) It should be remarked that the "varactor theory"[3] so far proposed for the separated medium configuration does not lead to the guiding principle of loss-less operation, because the final expression for the convolver efficiency is proportional to the attenuation of SAW.