Charge transfer by surface acoustic waves on a monolithic MIS structure

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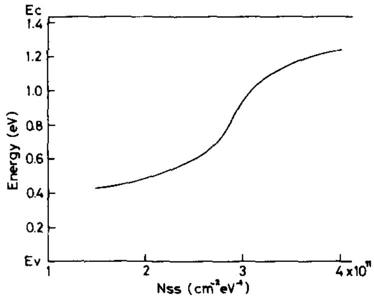

FIG. 3. Surface-state density distribution on (111)*B* *n*-GaAs surface derived from Fig. 2(b) by the high-frequency capacitance method.

C-*V* characteristics of MIS structures without a native oxide layer are shown in Fig. 2, where very little frequency dispersion in the positive bias region is observed, indicating true accumulation. Frequency dispersion observed in the as-deposited sample in Fig. 2(a) is again due to the dispersion of gallium oxy-nitride layer. This dispersion as well as hysteresis of *C*-*V* curves is very much improved in the sample annealed in the same condition as stated above, as shown in Fig. 2(b).

The high-frequency capacitance method to derive the distribution of surface-state density can be applied to the characteristic in Fig. 2(b), and the result is shown in Fig. 3.

The reduction of surface-state density would be speculated as follows. If the same order of dangling bonds are assumed for Ga and As atoms on the surface of GaAs, an As atom attracts an electron originally belonging to Ga for the larger electronegativity of As and then both atoms will be stabilized. This would be closely related to the general observations that there exists a smaller density of surface states on the clean surface of more ionic semiconductors. An oxygen atom adsorbed on the surface, however, attracts an electron of As for its larger electronegativity than As and then introduces the higher density of surface states due to unstable As.

We do not know at present the exact interpretation of the effect of sputter etching; it may just remove the native oxide or the incorporation of nitrogen onto the surface of GaAs may be essential, as suggested by the pileup of nitrogen at the interface revealed by AES analysis. This is under further investigation.

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Charge transfer by surface acoustic waves on a monolithic MIS structure

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We have observed the minority-charge signal transferred by surface acoustic waves (SAW) on a monolithic MIS structure. In the $Al/ZnO/SiO_2/p$-Si system, we have made new improvements on the configuration of input and output gates and the channel-stop bias ring along the transfer path, and on the method to prepare the deep-depletion mode by applying the pulse bias at the transfer channel. This type of charge-transfer device by SAW (monolithic SAW-CTD) seems to have some advantages compared with the separated-medium type so far examined.

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The use of surface acoustic waves (SAW) has been tried to eliminate a rather difficult fabrication of the phased segmented gate structure in conventional CCD. Gaalema *et al.*[1] and Schwartz *et al.*[2] have succeeded to observe the synchronous drag of minority carriers using a prototype of $LiNbO_3/p$-Si separated-medium structure. However, in the separated-medium structure, it is rather difficult to maintain stably a uniform air-gap spacing. On the other hand, Papanicolau and

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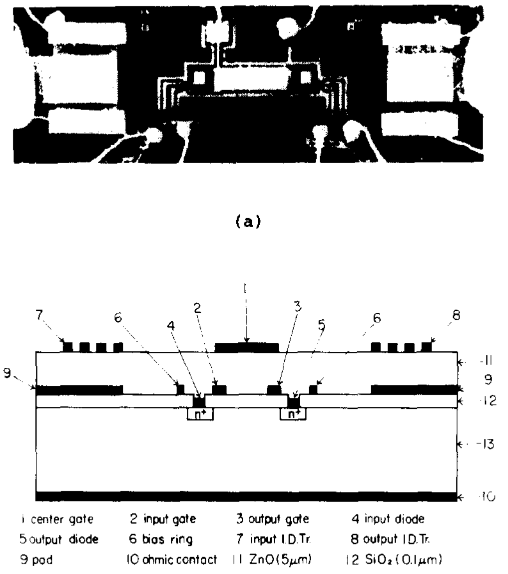

FIG. 1. (a) Photomicrograph and (b) schematic configuration of charge-transfer device by SAW (SAW-CTD). Diffusion depth and dimension of n^+ input and output diodes are 3—4 μm and 1.5×1.5 mm², respectively. Separation of the two diodes is 5 mm.

Lin[3] have proposed a monolithic structure of $ZnO/SiO_2/n$-Si; but they could not observe the transfered charge signal. It is noted here that there are two important points in the fabrication of the monolithic device. First, if there are dirty processes in the fabrication, the surface potential of Si cannot be modulated enough by SAW and also the transfered signal charge suffers a large loss due to the trapping by a large number of surface states in Si. Second, if there is no channel-stop structure, the transfered signal charge cannot be confined to the SAW propagation path.

Keeping the above two points in mind, we have carefully fabricated a MIS structure of $Al/ZnO/SiO_2/p$-Si. We have made new improvements on the configuration of the input and output gates and the channel-stop bias ring, and on the method to prepare the deep-depletion mode by applying the pulse bias at the transfer channel. We have succeeded to observe the minority-charge transfer by SAW.

The photomicrograph and the schematic configuration of the charge transfer device by SAW (SAW-CTD) on an $Al/ZnO/SiO_2/p$-Si structure are shown in Figs. 1(a) and 1(b), respectively.

The important fabrication processes of SAW-CTD are as follows:

(1) The gate oxidization (1000 Å) in dry O_2 (100 ppm H_2O) at 1050 °C after chemical etching of the PSG and SiO_2 mask for a selective diffusion, the photoengraving of contact windows, the evaporation of Al over all the surface, the annealing (30 min at 400 °C) in dry N_2 (100 ppm H_2O), and the photoengraving of Al for input and output gates, diode leads, bias ring, and pads under the interdigital transducers (IDT's). The annealing is the most important process to decrease the flatband voltage and the number of surface states at the Si surface over a large gate area (1.5×5 mm²).

(2) The dc sputtering of ZnO in dry O_2 (at 8.4×10^{-2} Torr) at 155 °C, where the thickness of ZnO was 5 μm, which corresponds to the first peak of the electromechanical coupling of SAW of 42 MHz.[4] The photoengraving of the center gate on ZnO where the lift-off technique was taken since an etchant of Al destructs the ZnO film.

In Fig. 2(a) the potential profile of the monolithic SAW-CTD is shown. We have used samples of p-Si {300—450 Ω cm, SAW propagation direction; $[\bar{2}11]$ on (111)}, since the surface of Si can be easily inverted in $Al/ZnO/SiO_2/p$-Si compared with the n-Si system.[5,6] When there is no bias, the surface of p-Si is inverted all over the sample. Therefore, the transfer channel must be separated by the depletion layer from the other part by using the dc bias at the bias ring as shown in Fig. 2(c).

The surface potential of the transfer channel under the center gate must be adjusted at deep depletion where

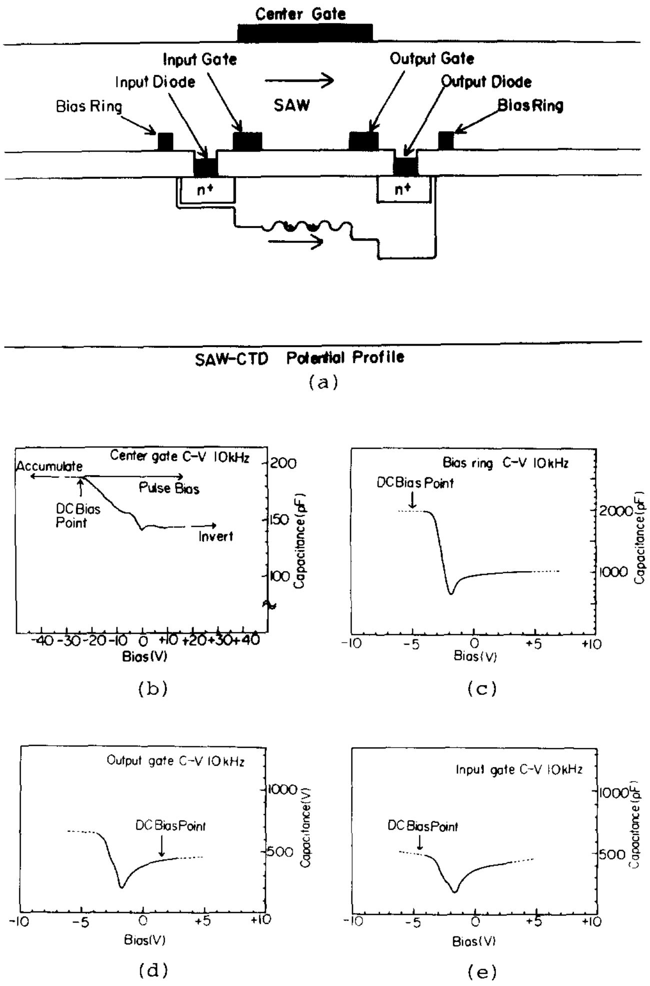

FIG. 2. (a) Potential profile of the monolithic SAW-CTD. C-V characteristics and bias points at operation of (b) center gate, (c) bias ring, (d) output gate, and (e) input gate.

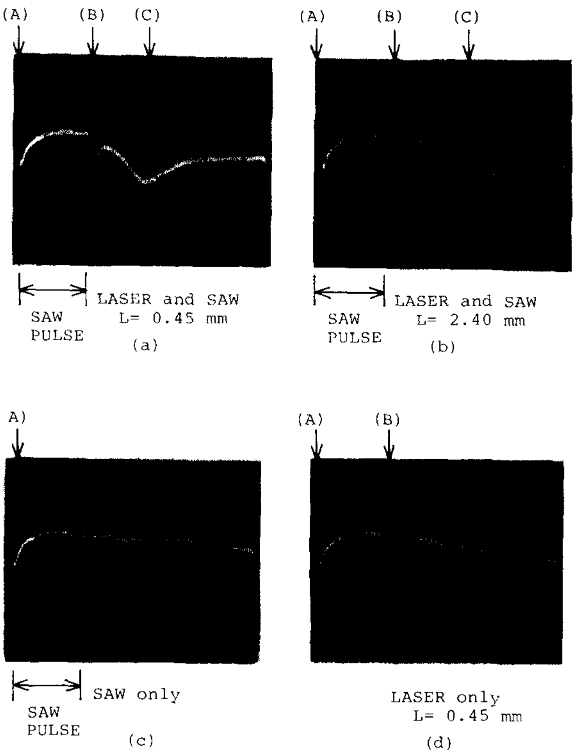

FIG. 3. Output diode current. (a) and (b): GaAs laser pulse (9040 Å) illumination and SAW (42 MHz) propagation, (c): SAW only, and (d): GaAs laser pulse only. Peaks (C) of (a) and (b) are the signals of the minority carriers injected by laser and transferred by SAW. Spikes (A) are due to a noise by the center gate pulse and (B) the pulse of laser diode. L is the distance between the laser spot and the output gate.

neither majority nor minority carriers exist at the Si surface. For this purpose, we used the (dc + pulse) bias method as shown in Fig. 2(b), where the rise time (1 μs) and the pulse width (10 μs) of the bias pulse are much shorter than the storage time (about 1 s). By using this method, we do not need the removal of minority carriers from the inversion layer by SAW, as used by Gaalema *et al.*[1]

The signals of the minority carriers injected by a GaAs laser at the center gate and transfered by SAW to the output diode (reverse biased at + 0.7 V) were observed at peaks (C) in Figs. 3(a) and 3(b), where L is the distance between the laser spot and the output gate. The pulse width of the laser (9040 Å) was 2.8 ns, which is much shorter than one period of SAW (42 MHz). The laser spot was focused to about 0.5 mm in diameter. The output current was measured through the band-rejection filter to detect the envelope of the transfered charge packet by SAW. The input gate was dc biased at the accumulation point as shown in Fig. 2(e) in order to reject the minority-carrier injection from the input diode to the transfer channel. The negative sign of the observed signals shows that the signals are due to the minority carriers (electrons). Spikes (A) are due to a noise by the pulse applied to the center gate and spikes (B) by the pulse of the laser diode.

When only SAW was launched, no signal peak was observed, as shown in Fig. 3(c). The small and gradual increase of the negative current observed seems due to the minority carriers thermally excited at the deep-depletion layer and/or the leakage through the bias ring and the input gate. When only the laser pulse was applied near the output gate there was no signal peak, as shown in Fig. 3(d). The gradual increase of the negative current in Fig. 3(d) was due to the diffusion transfer.

The transit time of the charge packet estimated from Figs. 3(a) and 3(b) was 0.8 μs across 1.95 mm, which gives a transfer speed of 2400 m/s, much lower than the group velocity of SAW (3200 m/s). This means that a part of the signal carriers was slipped out from the bunching potintial of SAW. We estimate the magnitude of the SAW potential wells at the surface of Si by a straightforward extention of the model of Kino and Wagers,[4] i.e., by taking into account the depletion layer at the surface of Si. When $\omega \ll \omega_c$ (ω: angular frequency of SAW, ω_c: dielectric relaxation frequency) and $W_d \ll \lambda$ (W_d: width of depletion layer, λ: wavelength of SAW), the SAW potential ψ_s at the surface of Si is given by

$$\psi_s = 2\frac{\epsilon_p/\delta_p}{(\epsilon_p/\delta_p + \epsilon_s/W_d)}\left(\frac{P_a}{\omega w_a\{\epsilon_s + \epsilon_p \coth[(2\pi/\lambda)(\epsilon_p/\epsilon_s)\delta_p]\}} \times \left|\frac{\Delta v}{v}\right|\right)^{1/2} = 0.45\ \text{V}, \tag{1}$$

where P_a (SAW power) $\simeq$ 10 mW (transducer efficiency $\simeq$ 21-dB loss), ϵ_p (permittivity of ZnO) = 9.0, ϵ_s (permittivity of Si) = 11.8, δ_p (thickness of ZnO) = 5 μm, $W_d \sim 5$ μm, $\omega/2\pi = 42$ MHz, $\lambda = 100$ μm, w_a (SAW beam width) = 1 mm, $|\Delta v/v| \simeq \frac{1}{2}k^2 = 0.0034$ (k: electromechanical coupling constant), and we neglect the oxide thickness (1000 Å) compared with that of ZnO.

The potential required to produce synchronous movement (bunching) of a charge with SAW is given by[7]

$$\psi_{ss} > v\lambda/2\pi\mu_n = 0.96\ \text{V}, \tag{2}$$

where v (velocity of SAW) = 4200 m/s and μ_n (surface mobility of electron) = 750 cm^2/V s. To realize the perfect bunching, the SAW power in the present experiment was insufficient.

Finally, we discuss the observed signal current level ($\simeq$ 9.7 μA). The injected carriers by the laser (1.8 W, 2.83 ns), when perfectly transfered, give the current peak of 12.8 μA, if the quantum efficiency is unity. The small value of the observed signal seems due to the slipping out from the bunching potential.

In conclusion, we have observed the minority-charge signal transfered by SAW on the monolithic Al/ZnO/SiO$_2$/p-Si structure. This monolithic SAW-CTD seems to have some advantages compared with the separated type so far examined. For example, the monolithic type is superior with regard to the uniformity and fabrication ease, since it is free from the difficulties of air-gap control. However, at the present level of the technology of piezoelectric thin-film fabrication, the separated type is superior with regard to the bandwidth, dynamic range, and temperature dependence.

Compared with a conventional CCD, the SAW-CTD has potential advantages, such as higher information density, higher speed, lower power consumption,[1,2] and uniformity, since the multilayered gate structure is unnecessary. However, the SAW-CTD has a disadvantage with regard to the dynamic range because of the small potential well.

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Internal electroabsorption in inverted heterostructures: An optical method for probing epitaxial layers

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Modulation internal electroabsorption was used to determine the gap energies and the presence of interface potentials of multilayered epitaxial n-n $GaAs_{1-x}Sb_x$ heterostructures. Experimental results indicate the presence of deep potential wells at the interface between epitaxial layers due to large net density of interface states. In addition to the observed band-to-band transitions in the epitaxial layers, it was possible to resolve transitions between filled and empty quantized states at the interface between the two epitaxial layers.

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Modulation electroabsorption (EA) and electroreflectance have been used extensively to study optical transitions in the band structure of solids.[1–4] In these experiments, the periodic perturbation of the electric field gives rise to changes in the optical dielectric function at photon energies at which optical excitation processes occur. In transmittance or reflectance, changes as small as 10^{-6} can be detected using the lock-in technique.[1] Semiconductors are ideally suited for these experiments since they already have built-in potentials at surfaces and p-n junctions which can readily be modulated by an external potential. Since in many instances the relationship between the modulated light signal and the type of potential barrier is well established,[5,6] modulation experiments are well suited to study the properties of such barriers. Information about surface potential, flatband potential, net carrier concentration, and material homogeneity can be readily obtained.[7–9]

It is the intent of this letter to report on recent experiments in which the electroabsorption technique was used to determined gap energies, carrier concentration, the nature of the built-in potential, and interface states in n-type $GaAs_{1-x}Sb_x$ heterostructures grown by liquid-phase epitaxy on (100) n^+ GaAs substrates. The important features of this experiment are shown schematically in the inset of Fig. 1. Monochromatic light is incident from the substrate or "window" side of the multilayered sample; the light penetrates and probes the thin epitaxial layers, is reflected internally at the metal contact, and is then detected by a photodiode or a photomultiplier. External dc bias V and a square-

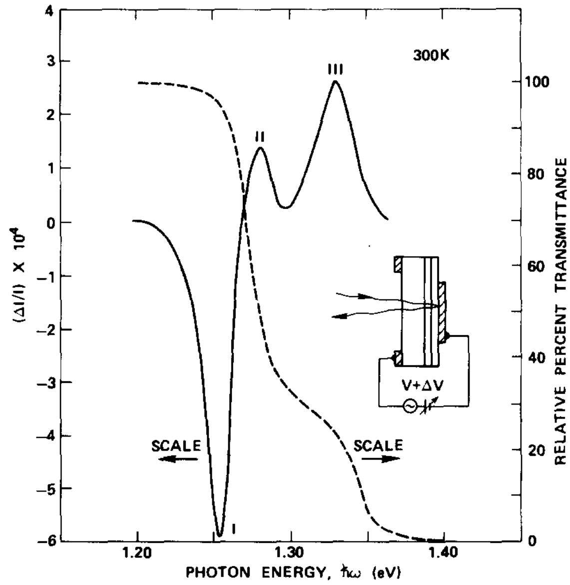

FIG. 1. Internally reflected field-modulated light intensity $\Delta I/I$ and relative transmittance at room temperature as a function of incident photon energy for the two-layer n-n $GaAs_{1-x}Sb_x$ heterostructure shown schematically in the inset. Experimental conditions: -1-V dc bias and 10-kHz 1-V_{pp} square wave modulation.

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