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Voltage tunable surface acoustic wave phase shifter on AlGaIn/GaN

J. Pedrós,^{1,a)} F. Calle,¹ R. Cuervo,¹ J. Grajal,² and Z. Bougrioua³

¹*Departamento de Ingeniería Electrónica and Instituto de Sistemas Optoelectrónicos y Microtecnología, Universidad Politécnica de Madrid, 28040 Madrid, Spain*

²*Departamento de Señales, Sistemas y Radiocomunicaciones, Universidad Politécnica de Madrid, 28040 Madrid, Spain*

³*Centre de Recherche sur l'Hétéroépitaxie et ses applications, CNRS, 06560 Valbonne, France and Institut d'Electronique, Microélectronique et Nanotechnologies, CNRS, Université de Lille, 59652 Villeneuve d'Ascq, France*

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A voltage tunable surface acoustic wave (SAW) phase shifter on a two-dimensional electron gas (2DEG) AlGaIn/GaN heterostructure has been developed. The acoustoelectric interaction is field-effect modulated by means of an insulated gate placed in the acoustic path of a SAW delay line. The phase velocity under the gate is tuned by modifying the conductance of the 2DEG with a dc bias, while the insulating layer prevents the screening of the SAW piezoelectric fields by the gate. The device is compatible with the nitride transistor technology for signal processing and frequency control applications. © 2010 American Institute of Physics. [doi:10.1063/1.3353971]

Surface acoustic wave (SAW) devices on AlGaIn/GaN heterostructures have recently attracted much attention. Their integration with the high electron mobility transistor (HEMT) technology is of particular interest for the development of monolithic microwave integrated circuits for signal processing and frequency control applications.¹ The insertion loss of a SAW filter on an AlGaIn/GaN system has been demonstrated to be governed, via the field effect, by the depletion of the two-dimensional electron gas (2DEG) underneath the interdigital transducers (IDTs).^{2,3} The piezoelectric transduction, screened initially by the 2DEG, is recovered when the IDTs, formed by Schottky contacts² or combinations of Schottky and Ohmic contacts,⁴ are reverse biased. In addition, the interaction of the electric fields accompanying the SAW with the mobile carriers of the 2DEG is expected to modify the phase velocity,⁵ as shown in voltage-controlled devices in GaAs/LiNbO₃ hybrids⁶ or AlGaAs/GaAs systems with a very deep 2DEG (0.5 μm).⁷ In these structures, the wave propagates close to the 2DEG but far from the gate, so the gate tunes the 2DEG without screening the SAW piezoelectric fields. However, this is not the case in the AlGaIn/GaN systems, where the 2DEG lies just 20–30 nm below the surface.

In this letter, a voltage tunable SAW phase shifter based on the acoustoelectric interaction in an AlGaIn/GaN structure containing a shallow 2DEG is reported. The efficiency of a thin insulating film, deposited below the control gate, as an acoustic spacer is demonstrated. The device is formed by a metal-insulator-semiconductor (MIS) diode with the insulated gate placed within the acoustic path of a SAW delay line, as depicted schematically in Fig. 1. The heterostructure, grown by metal organic vapor phase epitaxy on a c-sapphire substrate, consists of a 5.3-μm-thick GaN buffer layer followed by a 0.4–0.5-nm-thick AlN and a 25-nm-thick Al_{0.22}Ga_{0.78}N barrier layers, and capped with a 1.6-nm-thick GaN layer to prevent oxidation. Hall effect measurements

yielded a sheet carrier density N_s of $7.8 \times 10^{12} \text{ cm}^{-2}$ ($6.4 \times 10^{12} \text{ cm}^{-2}$ from C-V measurement at 50 kHz) and a mobility of 1930 cm²/V s. The Ohmic contacts of the diode were formed by a Ti/Al/Ti/Au multilayer annealed at 850 °C during 45 s in a N₂ atmosphere. A 300-nm-thick Si₃N₄ layer was then deposited by chemical vapor deposition at 300 °C and patterned by reactive ion etching using SiH₄:NH₃ and Ar:SF₆ mixtures, respectively. Finally, the gate contact of the diode and the IDTs were formed by a Pt/Ti/Au (10/5/100 nm) multilayer. The SAW delay line was aligned along the [11 $\bar{2}$ 0] direction of the sapphire substrate, which provides a non-pure sagittal Rayleigh mode.⁸ The IDTs have a period λ of 8 μm, a metallization ratio of 0.5, an aperture of 400 μm, and a delay length l of 3 mm. Both the Si₃N₄ acoustic spacer and the gate patterns have a trapezoidal shape to reduce the triple-transit interference. They have a length L of 1.75 mm and a width larger than the IDT aperture, so the whole wave front experiences the same delay. A similar device with $L=0.95 \text{ mm}$ and $l=2 \text{ mm}$ has been fabricated without the Si₃N₄ layer, i.e., forming a Schottky diode, for comparison purposes.

A fixed dc bias of −10 V has been applied to the IDTs in order to avoid the screening of the piezoelectric transduction by the 2DEG.² The selected bias is well below the threshold voltage $V_{th}=-3.8 \text{ V}$ indicated by the C-V characteristic of the IDTs (not shown). The depletion of the 2DEG underneath the transducers results in a 30 dB enhancement of the

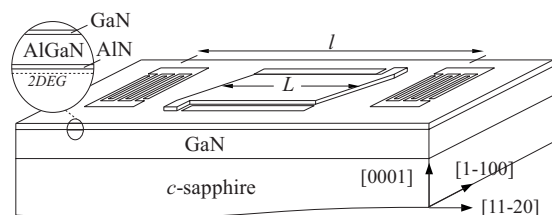


FIG. 1. Schematic of the voltage tunable SAW phase shifter on a 2DEG AlGaIn/GaN heterostructure. The device is formed by a MIS diode in the acoustic path of a SAW delay line. The inset shows a zoomed cross-section view of the top-most layers. The position of the 2DEG is indicated.

^{a)} Author to whom correspondence should be addressed. Electronic mail: jp495@cam.ac.uk. Present address: Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom.

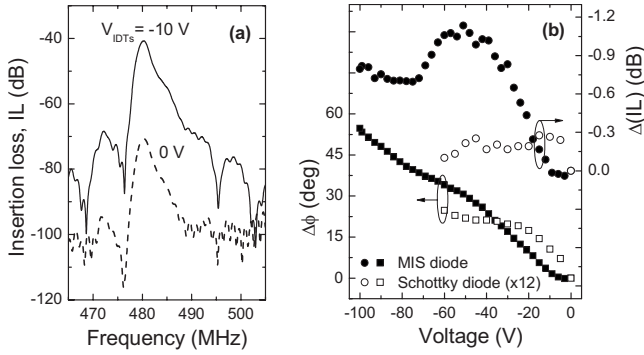


FIG. 2. (a) Modulation of the insertion loss IL of the SAW delay line when the IDTs are biased well below the threshold voltage of the structure, $V_{IDTs} < V_{th} = -3.8$ V. (b) Phase shift $\Delta\phi$ and insertion loss increase $\Delta(IL)$ induced by the MIS and Schottky diodes as a function of the voltage applied to them. The variations are referred to the values of the biased SAW delay line shown in (a).

strength of the transmitted acoustic signal, leading to an insertion loss IL of -40 dB at the resonance frequency, see Fig. 2(a). The remaining loss is mainly produced by the impedance mismatch of the IDTs, with an additional contribution from the mass loading due to the Si_3N_4 layer and the gate metal. The phase of the device is then tuned, from this reference state, by reverse-biasing the diode. The interaction of the electric fields accompanying the SAW with the 2DEG modifies the phase velocity and attenuates the wave. The normalized variation in the phase velocity v and the attenuation coefficient Γ are given by the expressions⁵

$$\frac{\Delta v}{v_0} = \frac{K_{\text{eff}}^2}{2} \frac{1}{1 + (\sigma/\sigma_m)^2}, \quad (1)$$

$$\Gamma = k \frac{K_{\text{eff}}^2}{2} \frac{\sigma/\sigma_m}{1 + (\sigma/\sigma_m)^2}, \quad (2)$$

where $k = 2\pi/\lambda$ is the wave vector, K_{eff}^2 is the effective electromechanical coupling coefficient, and σ is the sheet conductivity. $\sigma_m = v_0 \epsilon_{\text{eff}}$ represents the relaxation conductivity of the material at which the maximum attenuation occurs, where ϵ_{eff} is the effective dielectric constant of the layered structure. The variation in the phase velocity induces a phase shift given by

$$\Delta\phi = \frac{\Delta v}{v_0} \frac{2\pi L}{\lambda}, \quad (3)$$

where L is the length of the gate. On the other hand, the change in the attenuation coefficient leads to an attenuation of the transmitted intensity $I = I_0 \exp(-\Gamma L)$, that can be written as an increase in the IL as

$$\Delta(IL) = 10 \log(e^{-\Gamma L}). \quad (4)$$

The phase shift and the IL increase have been extracted from the transmission parameter S_{21} of the SAW delay line, whereas the dc conductance has been obtained from the I - V characteristic of the diode. Then, the values of $\Delta v/v_0$ and Γ arising from Eqs. (1) and (2) have been fitted to those obtained from Eqs. (3) and (4) with K_{eff}^2 and σ_m as fitting parameters. Figure 2(b) shows the phase shift and the IL variation as the gate bias is increased for the two SAW phase shifters under study. Notice that the data corresponding to the Schottky diode are scaled for an easier comparison. Thus, the

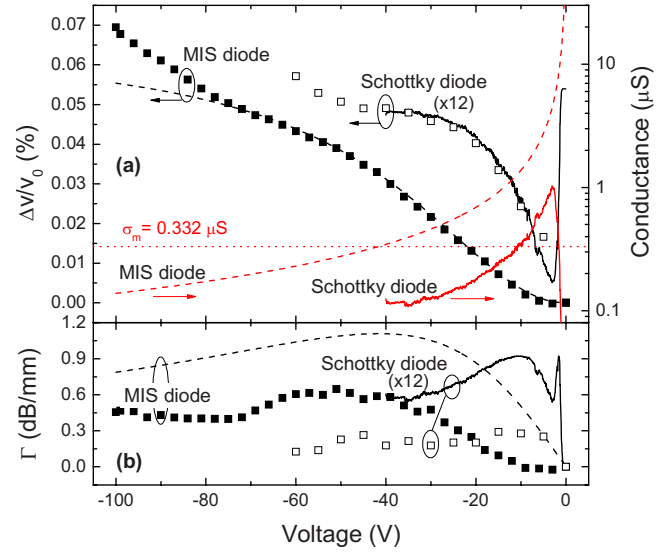


FIG. 3. (Color online) (a) Measured (symbols) and calculated (lines) normalized velocity change $\Delta v/v_0$ induced by the MIS and Schottky diodes, and the measured dc conductance as a function of the voltage applied to the diode. The horizontal dotted line indicates the value of σ_m arising from the fit. (b) Measured (symbols) and calculated (lines) attenuation coefficient Γ of both devices as a function of the bias applied to the diode.

MIS diode induces a much stronger phase shift, up to a value of 55° at -100 V, whereas the associated IL variation does not exceed -1.2 dB in any case. The particular dependence of both magnitudes with the bias is discussed below in the context of the electroacoustic relaxation model.^{5,9}

Figure 3(a) shows the normalized variation in the phase velocity in the MIS- and Schottky-diode-based SAW phase shifters and the dc conductance measured in both diodes, whereas Fig. 3(b) shows the attenuation coefficients. Notice again the scaling factor in the data corresponding to the Schottky diode. The fit of the experimental results to those calculated with the model described by Eqs. (1) and (2) points out the existence of two differentiated regimes. The low-reverse-bias regime, below approximately -40 and -80 V for the Schottky and MIS diodes, respectively, corresponds to the modulation of the 2DEG. The shift to higher bias in the MIS diode results from the series capacitance introduced by the Si_3N_4 layer, which is smaller than that of the 2DEG and thus determines the threshold voltage at which the depletion takes place.¹⁰ In this regime, there is a very good agreement between the measured and calculated evolution of the normalized variation in the phase velocity, whereas the attenuation coefficient is systematically overestimated. This mismatch might be related to diffusion effects that are neglected by the model, which actually assumes a Debye length λ_D much smaller than the thickness of the barrier layer.⁹ In fact, we estimate $\lambda_D \approx 10$ nm in our system for a background dopant density of 10^{17} cm^{-3} , which is comparable to the barrier thickness. Small discrepancies in the attenuation attributed to this mechanism have been also reported in thin-film ZnO systems.¹¹ The high-reverse-bias regime shows an additional increase in the normalized variation in the phase velocity superimposed to that predicted by the relaxation model for the 2DEG. Accordingly, Γ is no longer reduced as the reverse bias is increased. These effects are attributed to the modulation of the conductivity of the GaN buffer layer,¹² whereas a possible injection of carriers from the gates seems improbable since no significant in-

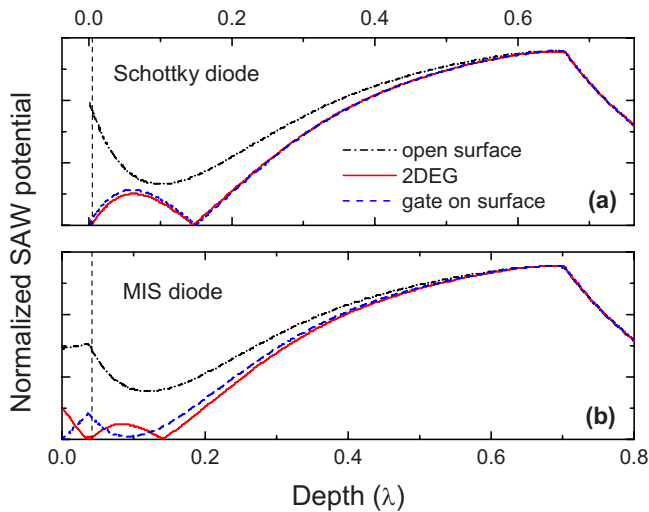


FIG. 4. (Color online) Normalized SAW potential as a function of the depth (in units of the wavelength) calculated for the (a) Schottky-diode- and (b) MIS-diode-based SAW phase shifter under different boundary conditions. The vertical dashed line indicates the position of 2DEG within the layered structure.

crease on the leakage current of the diodes is observed in this regime.

The fitting parameters used in Figs. 3(a) and 3(b) are $\sigma_m = 3.32 \times 10^{-7}$ S, $K_{\text{eff}}^2 = 0.13\%$ for the MIS diode and 0.009% for the Schottky diode. The value of K_{eff}^2 in the structure containing the insulating spacer layer agrees well with the value of 0.10% extracted from the S parameters using the equivalent circuit of an IDT in the crossed-field model,¹³ and that calculated for the GaN/sapphire structure.¹⁴ However, the value of K_{eff}^2 in the structure without insulator is much smaller as a consequence of the close vicinity of the gate to the 2DEG, so the field-effect modulation of the sheet conductivity is masked by the high conductivity of the metal.

The effect of the Si_3N_4 layer on the depth profile of the SAW potential is shown in Fig. 4. The SAW potential under the diodes has been calculated for three different boundary conditions: a non-metallized or *open* surface, a metallized surface (gate), and a conducting plane at the AlN/GaN interface (2DEG). Conversely to the Schottky diode case, Fig. 4(a), where the latter two conditions are almost indistinguishable, they are clearly different in the case of the MIS diode, Fig. 4(b). Thus, the insulating spacer layer permits to tune the conductivity of the 2DEG system, preventing the SAW fields to be reduced by the gate contact. A tailored decrease in λ and in the thickness of the spacer layer is foreseen to provide a larger phase shift range at lower voltages without increasing the gate length. In addition, the dependence of Γ on k is expected to become sublinear with increasing frequency,⁵ counteracting the increase in the at-

tenuation produced by the slightly higher K_{eff}^2 when reducing λ . On the other hand, a small variation in the bias applied to the IDTs may permit a simultaneous modulation of the gain of the signal. This could ensure, for example, the near-class-A operation in a voltage-controlled SAW oscillator.

In conclusion, we have demonstrated a voltage tunable SAW phase shifter on a 2DEG AlGaIn/GaN heterostructure. The acoustoelectric interaction is field-effect modulated by means of a MIS diode in the path of a SAW delay line. The gate tunes the conductivity of the system, whereas the insulating spacer layer prevents the shortening of the SAW electric fields. In addition to its application to voltage-controlled SAW phase shifters and oscillators, this device is compatible with the AlGaIn/GaN HEMT technology, allowing its integration into MMICs.

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