

LARGE GAIN IN GATED MONOLITHIC SURFACE ACOUSTIC WAVE AMPLIFIER ON HETEROGENOUSLY INTEGRATED III-V EPITAXIAL SEMICONDUCTOR AND LITHIUM NIOBATE

***REMEMBER THAT NO NAME OF AUTHORS AND/OR INSTITUTIONS SHOULD APPEAR ON
THIS ABSTRACT, AS IT IS PREPARED FOR A DOUBLE-BLIND REVIEW (DBR) PROCESS!***

Novelty/ Progress Claims

This paper demonstrates a monolithic surface acoustic wave (SAW) amplifier fabricated by state-of-the-art heterogenous integration of a III-V indium gallium arsenide (InGaAs)-based epitaxial material stack and lithium niobate (LiNbO₃). There is a three-fold increase in electronic gain compared to previous demonstrations with a reduced power consumption. Additionally, gate electrode placement enables effective control over gain by modifying pinch off effects. This platform will then enable further advances in active and non-reciprocal piezoelectric acoustic devices.

Background/ State of the Art

Active and non-reciprocal piezoelectric acoustics has the potential to transform RF signal processing by miniaturizing devices such as amplifiers, circulators, isolators, switches, and oscillators. These active devices operate based on the acousto-electric effect, which has been harnessed experimentally for surface acoustic wave (SAW) amplifiers since the 1960s with demonstrated electronic gain values exceeding 100 dB/cm [1-5].

However, there are challenges to fabricate chip-scale, monolithic devices integrating both high-performing semiconductor and piezoelectric materials. The semiconductor must have a low doping concentration to prevent screening of the acousto-electric interaction, high mobility such that gain is obtained at lower voltages, and low defectivity. The piezoelectric must have a high electromechanical coupling coefficient (k^2). In addition, high power consumption made practical implementations of these devices unobtainable.

Current research in non-reciprocal acoustic devices is focused on the integration of 2D electron gas (2DEG) systems [6,7] and 2D semiconductor materials [8], but experimental gain has fallen short of expectations typically due to low k^2 values. **More recent works using thin films at lower carrier densities suffer gain saturation due to pinch-off effects of mobile carries and gated electrodes.** Here we present, for the first time, a SAW amplifier based on the integration of lithium niobate (LiNbO₃) with epitaxially grown indium gallium arsenide (InGaAs). This platform leverages recent advances in the fields

of epitaxial semiconductor materials and heterogenous integration to enable chip-scale devices with high gains at lower voltages and therefore lower power dissipations. **Additionally, using the transducer as a gate can counteract pitch off making large gain with low carrier density possible.**

Description of the New Method or System

Here a SAW amplifier is presented that is fabricated by heterogenous integration of a III-V epitaxial semiconductor material stack with a LiNbO₃ piezoelectric acoustic delay line. InGaAs is chosen due to its high mobility and controllable doping during the metal-organic chemical vapor deposition (MOCVD) growth while LiNbO₃ is chosen due to its high k^2 , required for high gain values. In addition, the two materials are integrated in a way to preserve these optimal material properties.

A schematic of the SAW amplifier presented in this work is shown in Figure 1. The devices consists of two SAW transducers with a rectangular InGaAs layer in the center. Electrical contact is made to the InGaAs by contact pads that terminate as strips along each end of the patterned semiconductor. A voltage applied to the interdigital transducer (IDT) acts as a gate for additional tuning.

The developed fabrication flow is shown in Figure 2. After wafer bonding, the epitaxial layers are selectively patterned and etched to form the amplifier and contact structures. Successful wafer-scale bonding is attributed to the quality and flatness of the epitaxial stack, which is evaluated by atomic force microscopy scans as shown in Figure 3a. A wafer-scale image and single SAW device SEM image are shown in Figures 3b and 3c, respectively.

Experimental Results

To measure gain in these devices, a RF signal was applied and the S_{21} value at the operating frequency of the device was measured using a spectrum analyzer (RS305) with respect to time during the application of a voltage pulse. A typical result with low gain is shown in figure 4 which shows the signal increase, phase shift and induced current during a measurement sequence and indicates the degree of measurement fidelity in this study. Figure 5,

demonstrates device performance with the application of a voltage pulse to the gate for a short and a long device. As shown in the figure the measured S_{21} value increases with the application of a gate voltage by 50dB/cm in the short device and by nearly 250 dB/cm in the long device. These results show that the placement of the gate electrode can readily offset pinch-off effects that have limited performance in prior works. Finally we show a figure of 43dB of gain in a long device. VLarge gains at lower voltages in a chip-scale device makes this platform a promising candidate for advanced non-reciprocal RF signal processing applications.

Word Count: 591

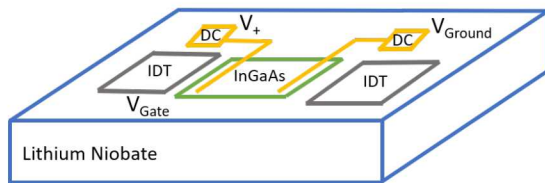
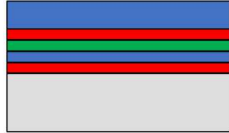
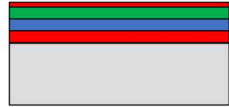


Figure. 1: Schematic of the InGaAs-LiNbO₃ heterostructure SAW amplifier.

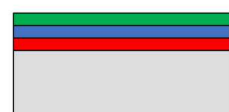
1. Bond InP substrate with epitaxial layers to LiNbO₃



2. Wet etch removal of InP



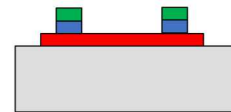
3. Wet etch removal of InGaAs stop etch layer



4. Pattern and etch InP contacts



5. Pattern and etch InGaAs amplifiers



6. Metal patterning, deposition, and liftoff for SAW transducers and semiconductor contacts

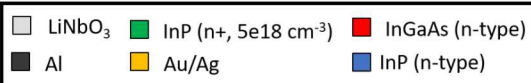
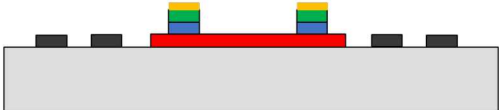


Figure 2: Process flow utilizing a III-V epitaxial semiconductor stack bonded to a y-cut LiNbO₃ wafer.

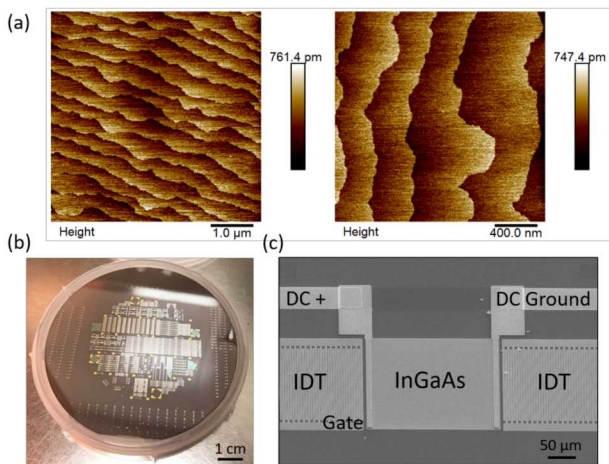


Figure 3: (a) AFM scans of the epitaxial stack before bonding to the LiNbO₃ wafer. (b) Wafer-scale image taken after processing. (c) SEM image of a single SAW amplifier device.

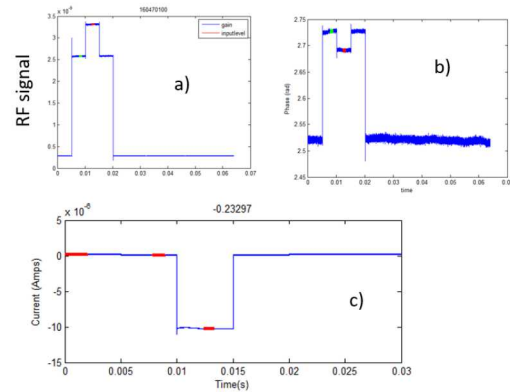


Figure 4: SEM micrograph showing details of the device.

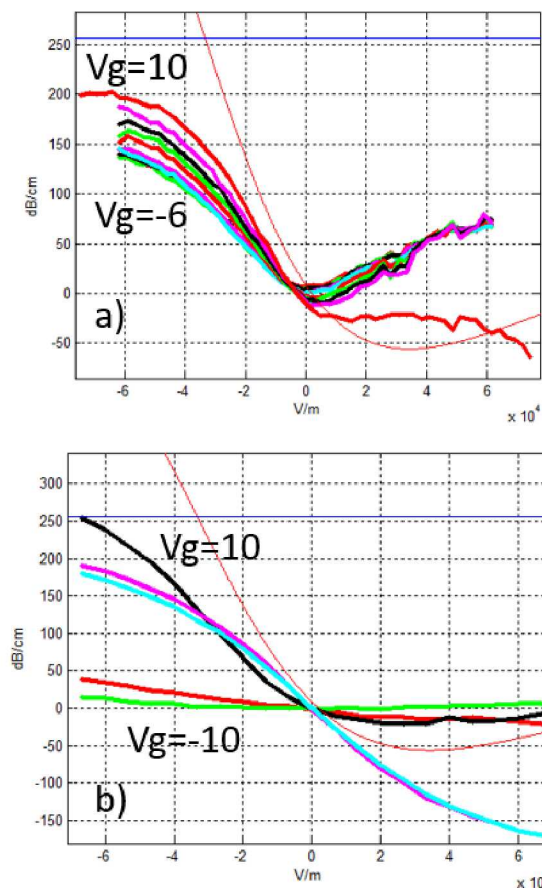


Figure 5: Gain in a short device, 78micron, (a) and long device, 150micron (b).

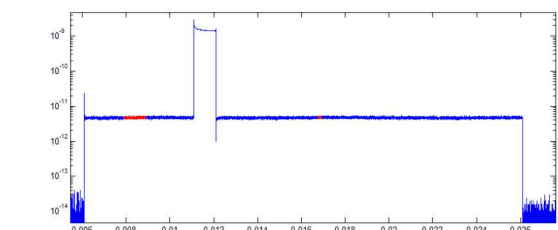


Figure 6: (a) Large gain 40dB achieved in a long device.

REFERENCES:

- [1] A. R. Hutson, J. H. McFee, D. L. White, "Ultrasonic Amplification in CdS", *Physical Review Letters* 7 (6) 237-239, 1961.
- [2] J. H. Collins, K. M. Lakin, C. F. Quate, H. J. Shaw, "Amplification of acoustic surface waves with adjacent semiconductor and piezoelectric crystals", 13 (9), 314-316, 1968.
- [3] L. A. Coldren, G. S. Kino, "The InSb on a piezoelectric Rayleigh wave amplifier", 21 (7), 421-427, 1974.
- [4] K. Yoshida, M. Yamanishi, "Interaction between surface elastic waves and drifting carriers in layered system", *Japanese Journal of Applied Physics*, 7, 1143-1144, 1968.
- [6] L. Shao, K. P. Pipe, "Amplification and directional emission of surface acoustic waves by a two-dimensional electron gas", *Applied Physics Letters*, 106, 023106, 2015.
- [7] H. Zhu, M. Rais-Zadeh, "Non-reciprocal acoustic transmission in a GaN delay line using the acoustoelectric effect", *IEEE Electron Device Letters*, 38 (6) 802-805, 2017.
- [8] Z. Insepov, E. Emelin, O. Kononenko, D. V. Roshchupkin, K. B. Tnyshtybayev, K. A. Baigarin, "Surface acoustic wave amplification by direct current-voltage supplied to graphene film", *Applied Physics Letters*, 106, 023505, 2015.