SAND2019-9676C

LARGE ACOUSTOELECTRIC EFFECT IN WAFER BONDED INDIUM GALLIUM ARSENIDE / LITHIUM NIOBATE HETEROSTRUCTURE

Aleem M. Siddiqui[1], Lisa P. Hackett[1], Daniel Dominguez[1], Anna Tauke-Pedretti[1], Tom Friedmann[1], Gregory Peake[1], Michael R. Miller[1], James K. Douglas[1], and Matt Eichenfield[1]

[1]Sandia National Laboratory, Albuquerque, NM, USA

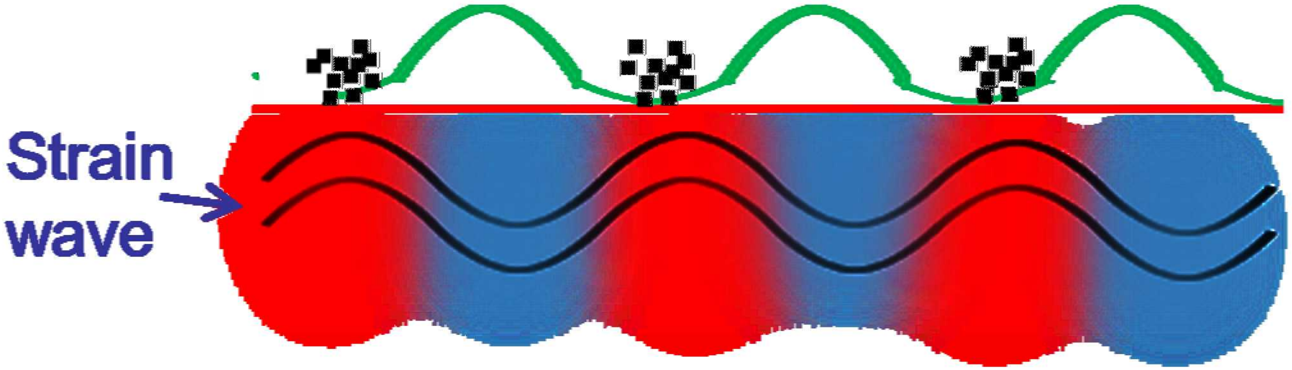
Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-003525.

Outline

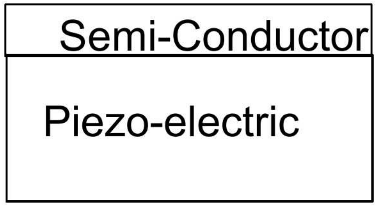
- ❑ Introduction
- ❑ Fabrication
- ❑ Demonstration of large gain
  - → Rayleigh Wave
  - → Leaky SAW – Terminal Gain
- ❑ Power Optimization
- ❑ Conclude

Acoustoelectric (AE) Interaction

- Carriers and surface acoustic wave (SAW) interact though a mutual quasi-static electric potential due to piezoelectricity



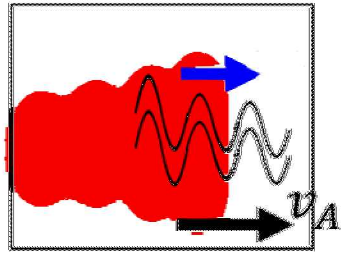
Material stack



to attenuation/gain

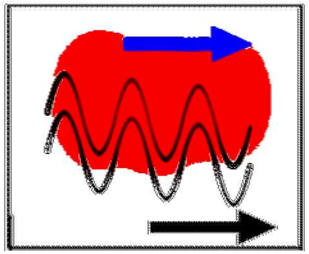
Attenuation

$v_e < v_A$



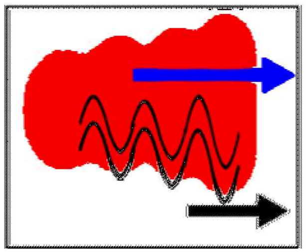
No loss

$v_e = v_A$



Amplification

$v_e > v_A$



$$P_{out} = P_{in} e^{\Gamma L}$$

$$\Gamma = K^2 \frac{\pi}{\lambda} \times \frac{x}{1 + (x)^2}$$

$$x = \left(\frac{v_A - \mu E}{v_A} \right) \frac{\sigma_m}{\sigma}$$

$$\sigma_m = (\varepsilon_P + \varepsilon_0) v_A$$

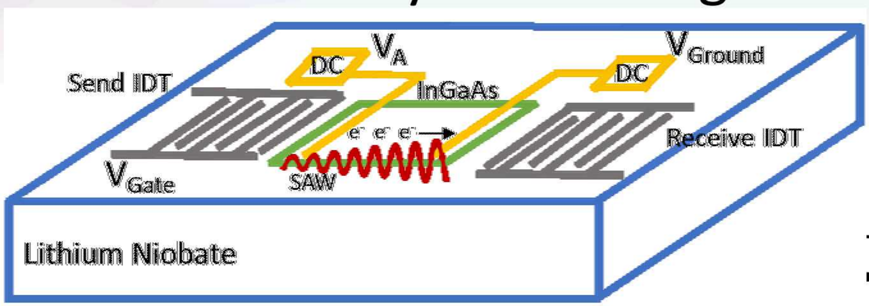
Sheet conductivity

: $\sigma = en\mu \times d$

Electro mechanic coupling: K_T^2

Gain Dependence on Electric Field

- Gain in a delay line through the AE effect



$$\Gamma = K^2 \frac{\pi}{\lambda} \times \frac{x}{1+(x)^2} \qquad x = \left(\frac{v_A - \mu E}{v_A}\right)\frac{\sigma_m}{\sigma}$$

$$P_{out} = P_{in} e^{\Gamma L}$$

- Max Gain Dependence and Voltage Requirements

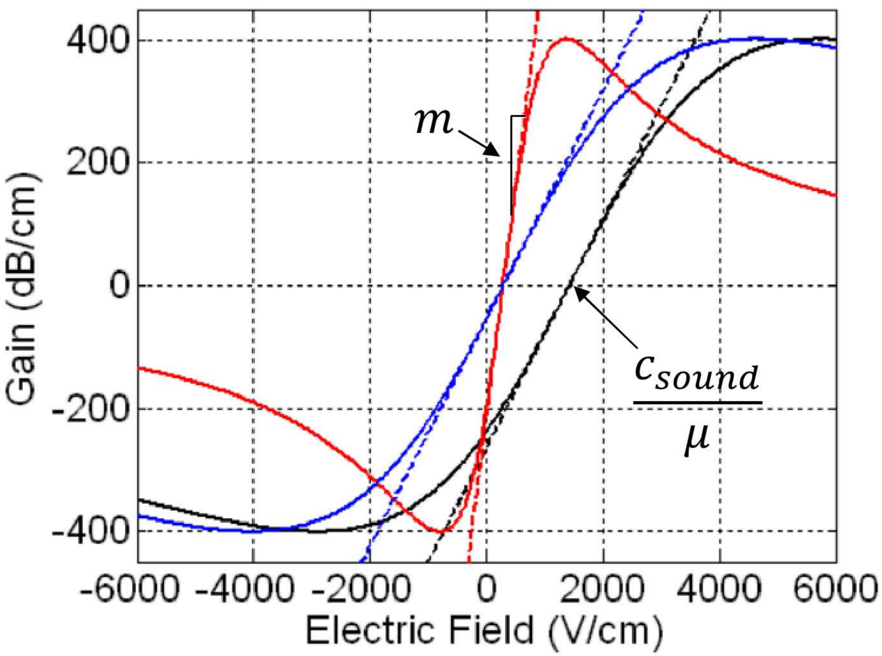
$$Gain_{max} = \frac{1}{4} K_{eff}^2 k_0 \times 4.3 \times 10^{-3} \quad [db/cm]$$

$$E_{max} = \frac{c_{sound}}{\mu} + \frac{q \times \rho_{carriers} \times d_{SemiConductor}}{\varepsilon_{eff}}$$

Match speed of sound

Extra field to get to max gain

$$V_{Tot} = V_{0dB} + \Delta V_{dB} \qquad \Delta V_{dB} = \frac{dB_T}{m},$$



$$m = 0.0869 \times K_r^2 \frac{\pi}{\lambda}\left(\frac{\varepsilon_P + \varepsilon_0}{d \times e \times n}\right)$$

Low voltage

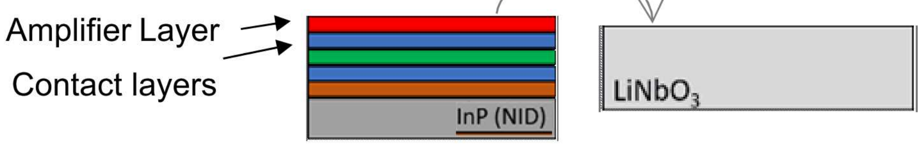
- High mobility
- Low Doping
- Mode with large K_T^2

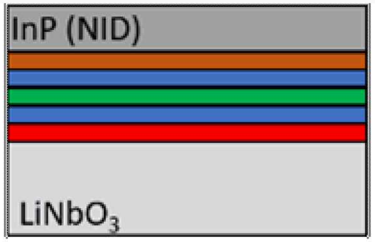
→Epitaxial InGaAs on Lithium Niobate

Fabrication Flow

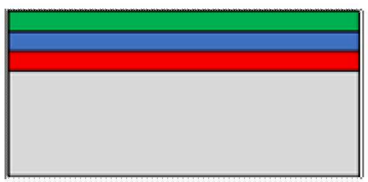
- Process flow utilizing a III-V epitaxial semiconductor stack bonded to a Y-cut LiNbO3 wafer

1. Bond InP substrate with epitaxial layers to $LiNbO_3$

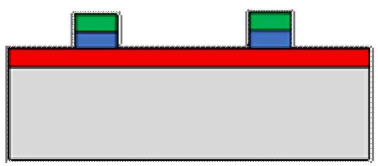




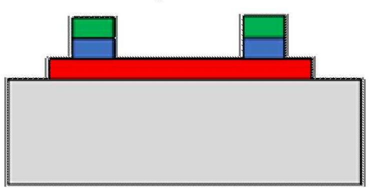
2. Wet etch removal of InP buffer, InGaAs, and InP etch stop layer



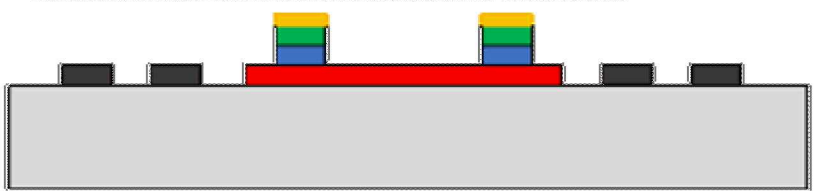
3. Pattern and etch InGaAs/InP contact layers



5. Pattern and etch InGaAs amplifiers

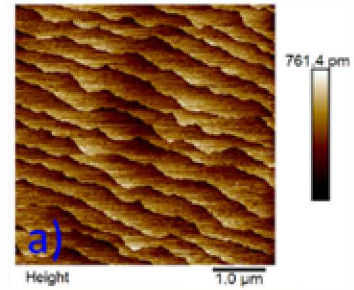


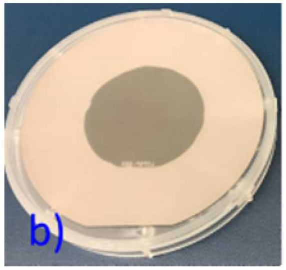
6. Metal patterning, deposition, and liftoff for SAW transducers and semiconductor contacts



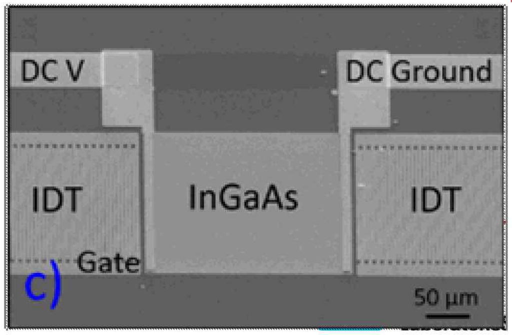
InGaAs (NID) | InP (n+, 1e18 cm^{-3}) | InGaAs (n+, 2e19 cm^{-3}) | Al | Au/Ag
InGaAs (n, 4e15 cm^{-3}) | $LiNbO_3$ | InP (NID)

Flatness and bonding completeness

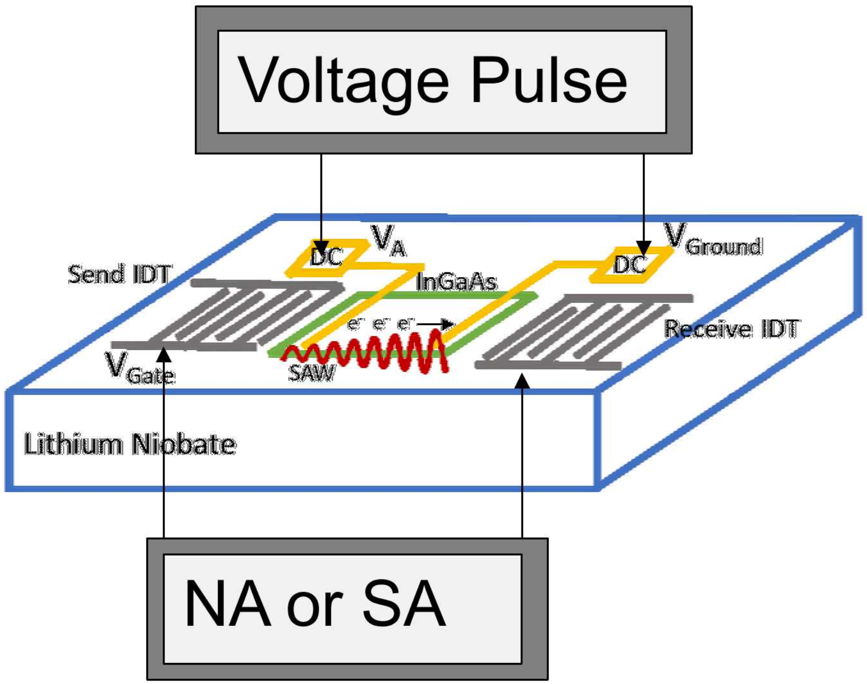


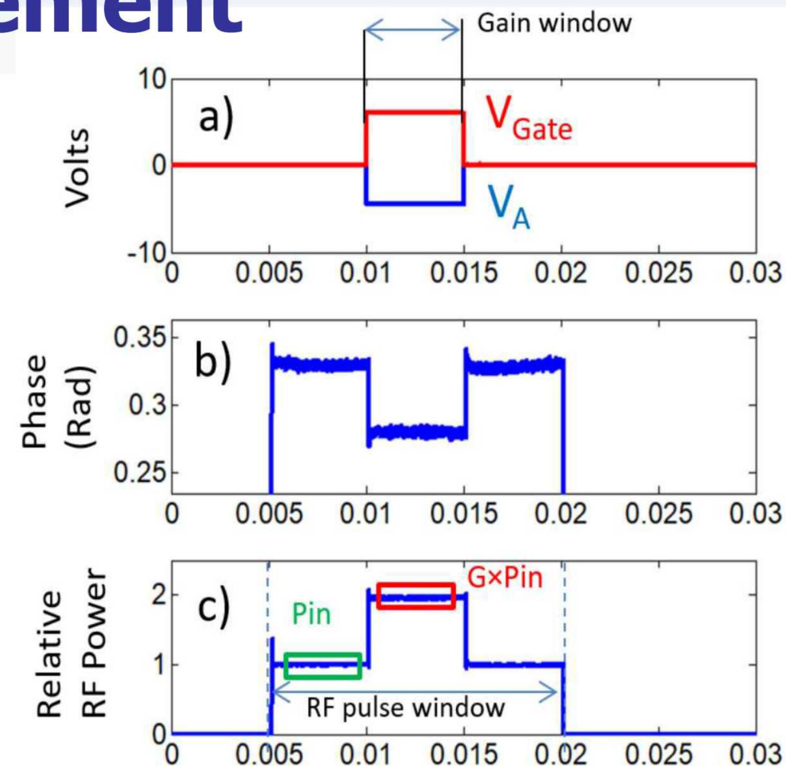


SEM of Device



Device Characterization and Measurement





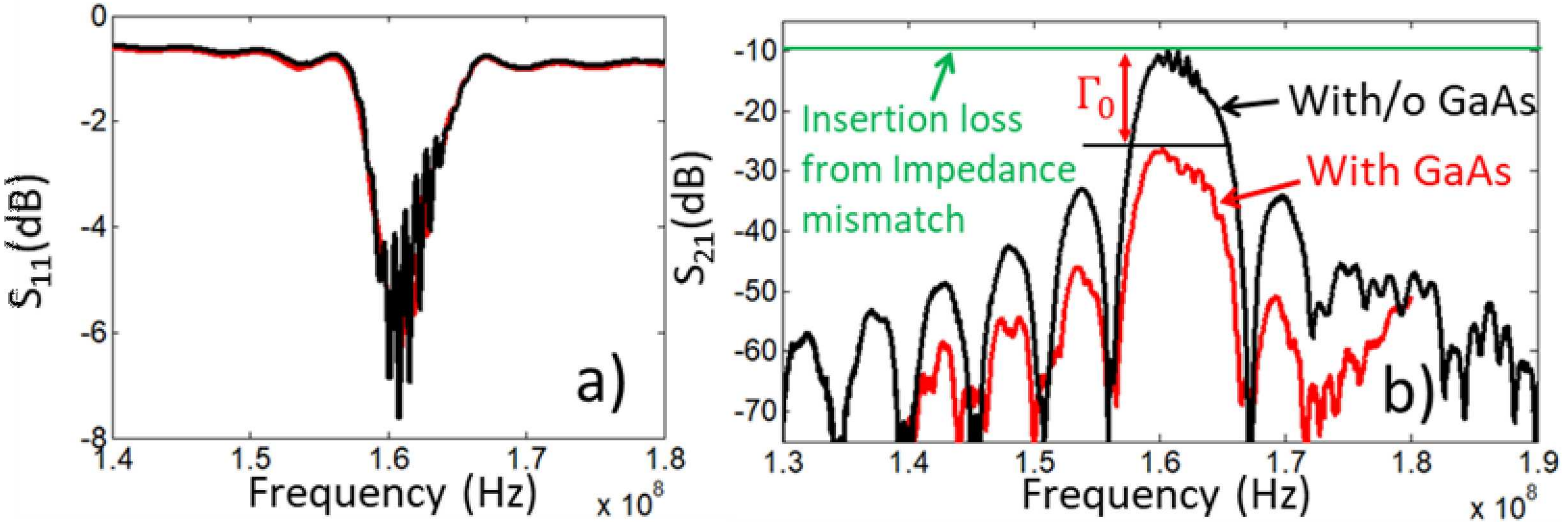
- ❑ RF and electrical resistance measurements set system parameters.

μ $\quad n_d$ $\quad \sigma = en\mu \times d$ $\qquad \lambda \quad K_T^2 \quad IL \quad v_A \quad \sigma_m$

  - ❑ Impedance matching
  - ❑ Pulsed Gain
  - ❑ Electrical and capacitive measurements.

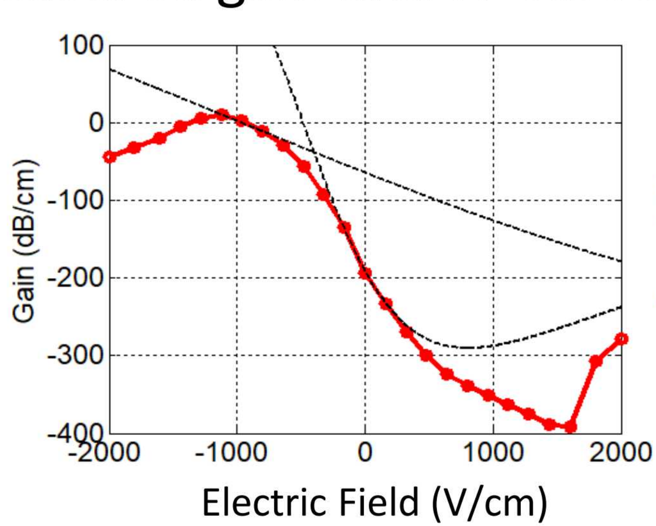
Device Design for Y-cut Z-Propagating

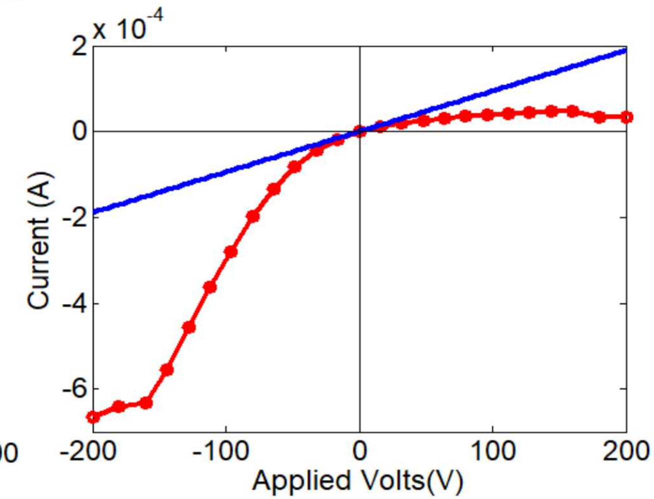
- ❑ Impedance matching in Send Receive Device: L=1mm, $N_{fingers}$ =60, pitch=10.5μm, Aperture=210μm



Zero-field attenuation: $\Gamma_0 = -214\mathrm{dB/cm}$

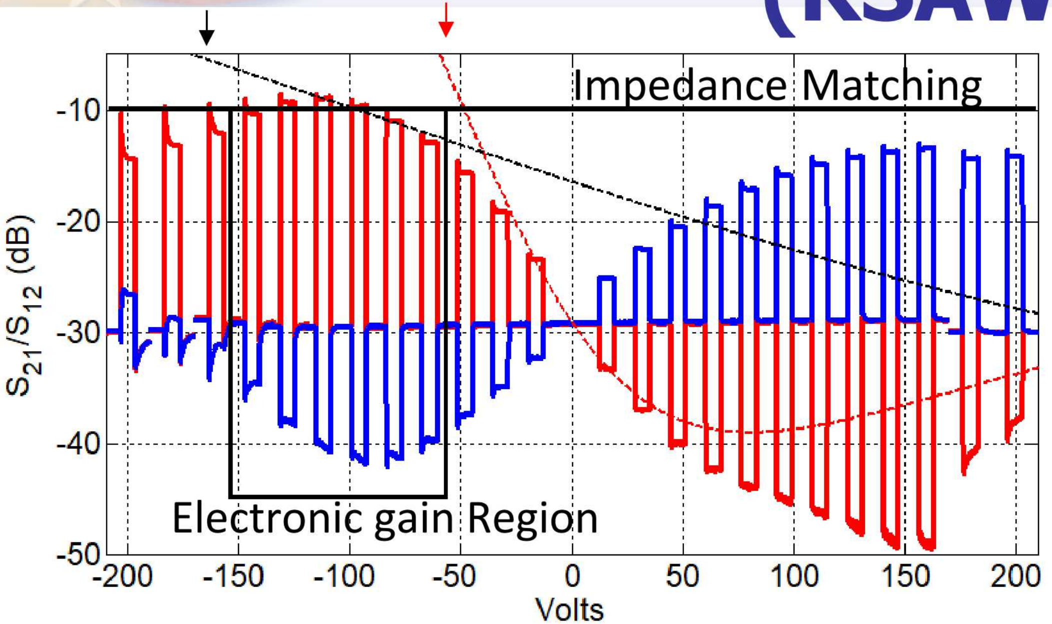
- ❑ Measured gain and IV curve

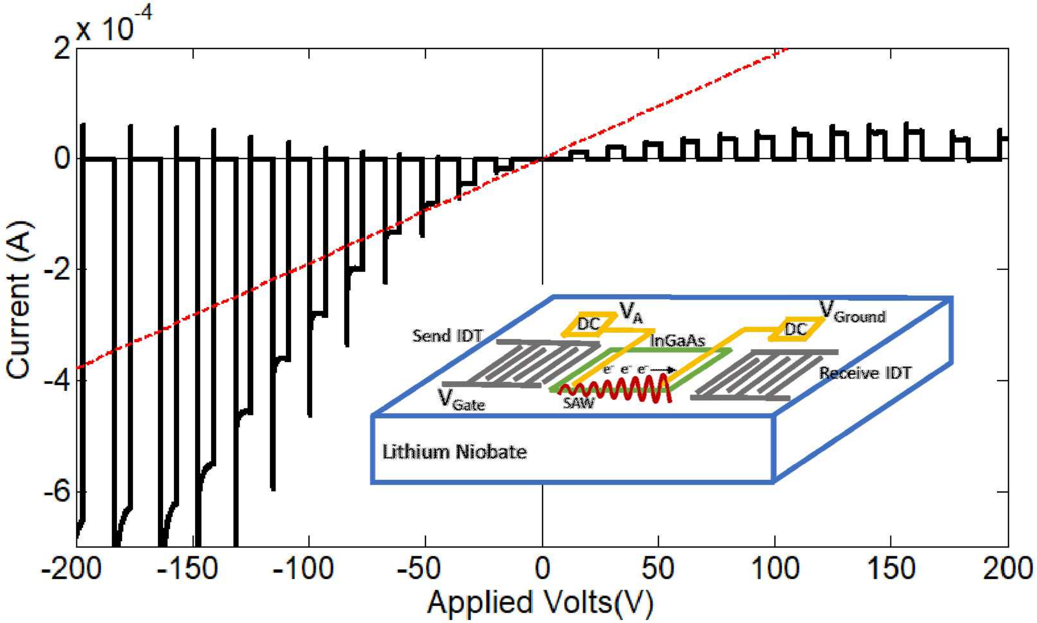




Sandia National Laboratories

Electronic Gain With Rayleigh SAW (RSAW)





- ❑ Electronic gain achieved
  - → Zero field attenuation to extrapolate gain predicts large gain

$$n_d = 4e15cm^{-3}$$

$$\mu = 702\mathrm{cm}^2/\mathrm{V}$$

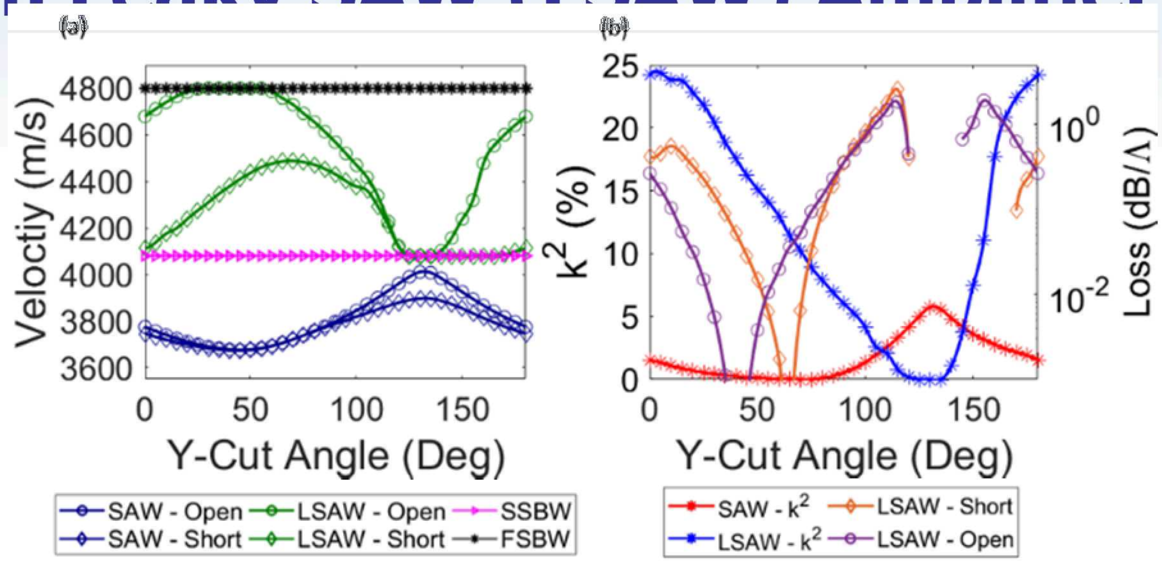
  - → Used measured conductivity with half mobility to rationalize loss of gain

Gain may be limited due to pinch off effects, band bending or thermal effects

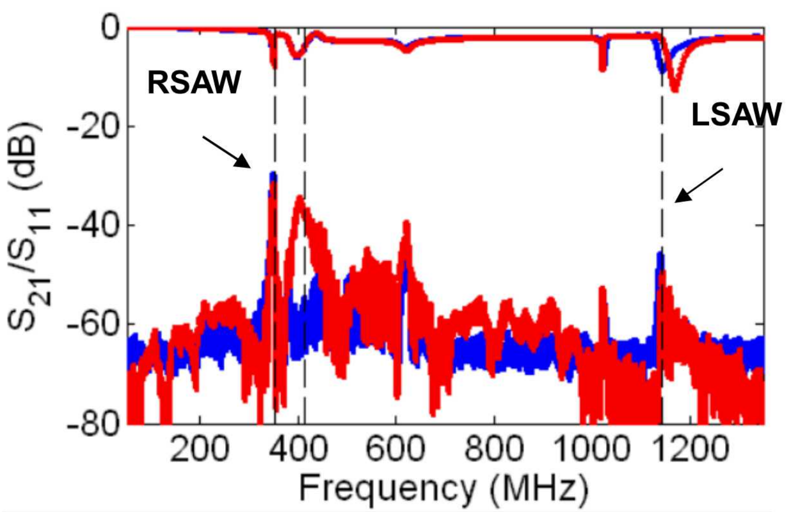
Sandia National Laboratories

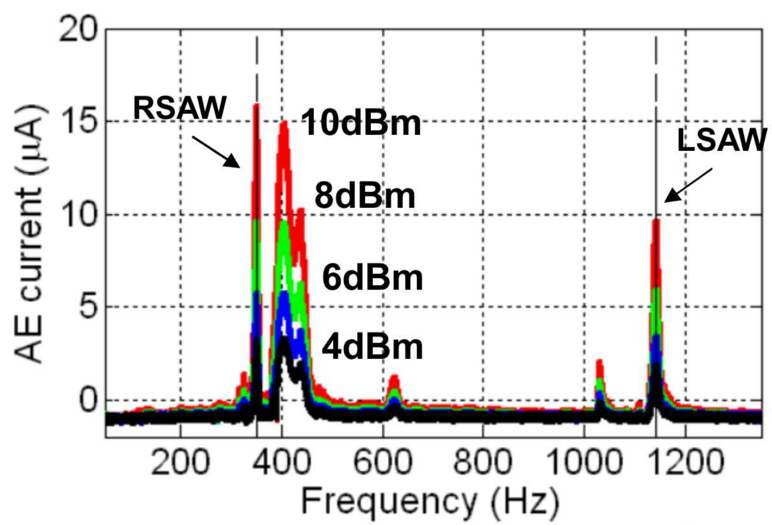
Y-Cut X-propagation Leaky SAW (LSAW) Amplifier

- LSAW has large K_T^2
  - 0^o: large K_T^2 dbut large loss.
  - 41^o or 64^o cuts
- AE gain must be large to counteract propagation loss



- Device Design: Amplifier: Length=1mm, Width=429µm,
  Transducer: $N_{fingers}$ =90, pitch=50µm,Aperture=210µm

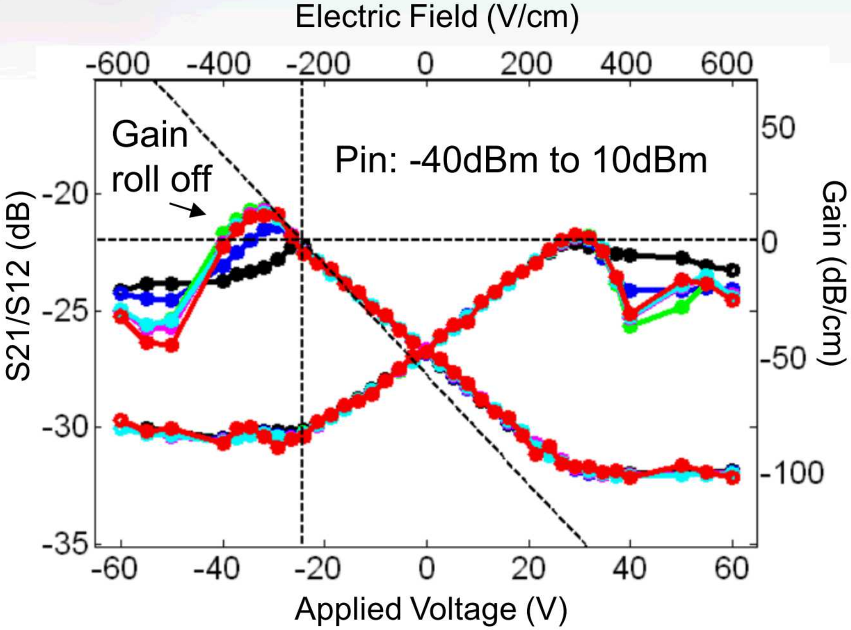




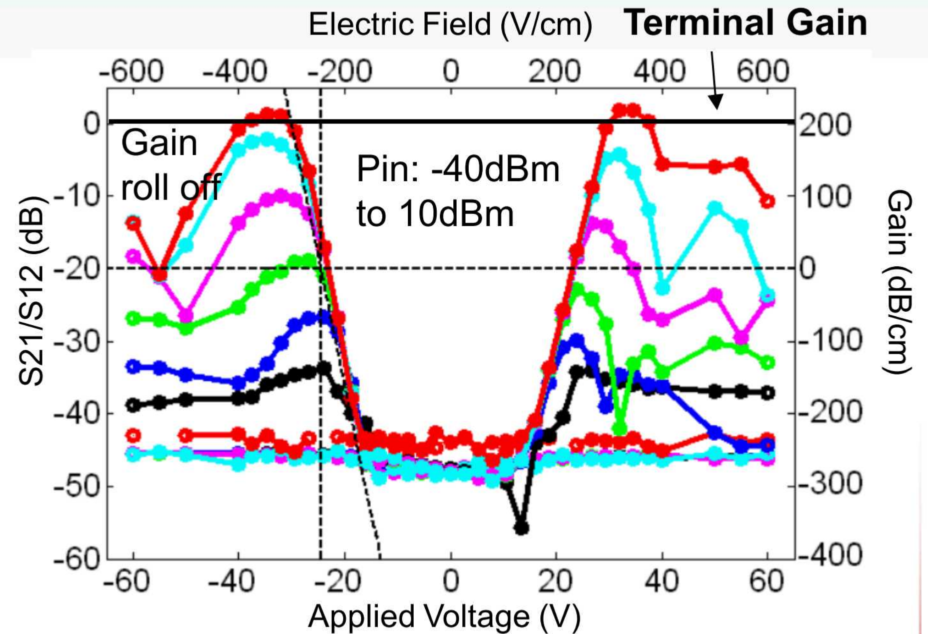
ndia
tional
boratories

Comparison Between SAW and LSAW

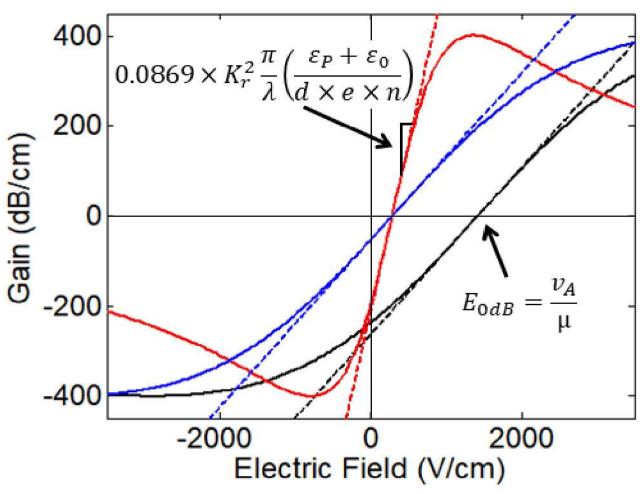
RSAW



LSAW



- ❑ Gain Comparison



- dB=0 position is fixed by mobility
- Slope increase by a factor of 5

$$K_{LSAW}^2 \ \ nearly\ 5 \times K_{RSAW}^2$$

$$\mathrm{n_d} = 20e15cm^{-3}$$

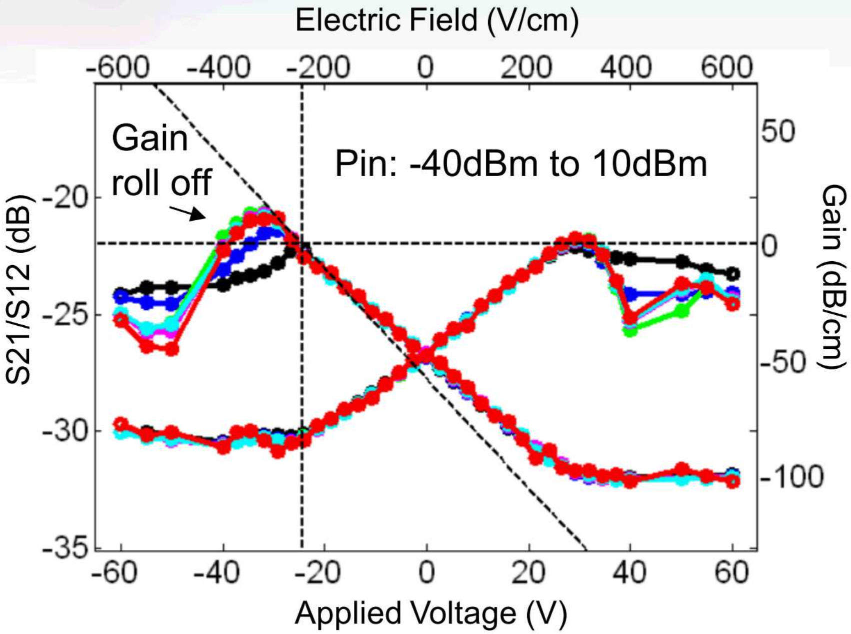
$$\mu = 1700\mathrm{cm}^2/\mathrm{V}$$

- Terminal gain of 3dB

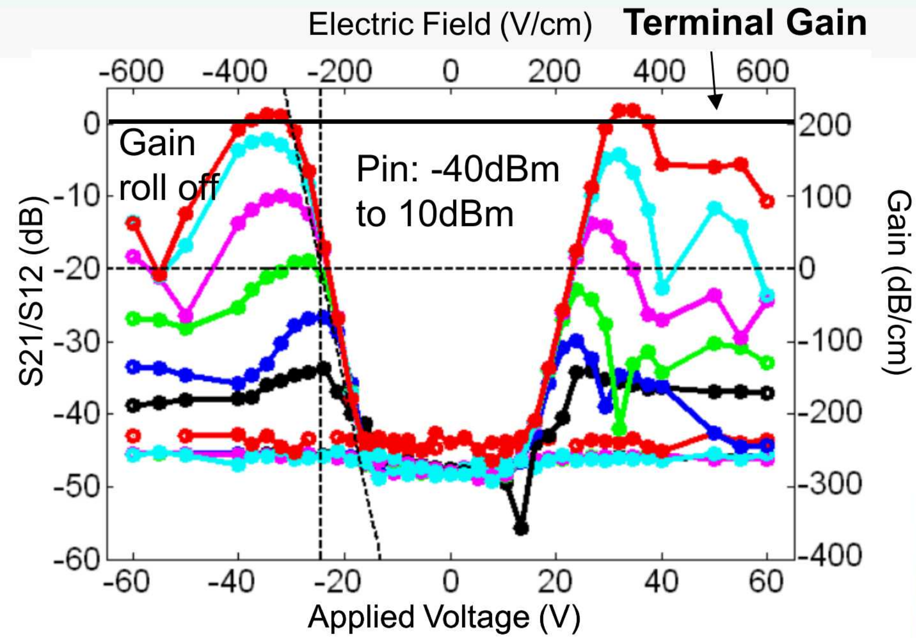
Sandia National Laboratories

Comparison Between SAW and LSAW

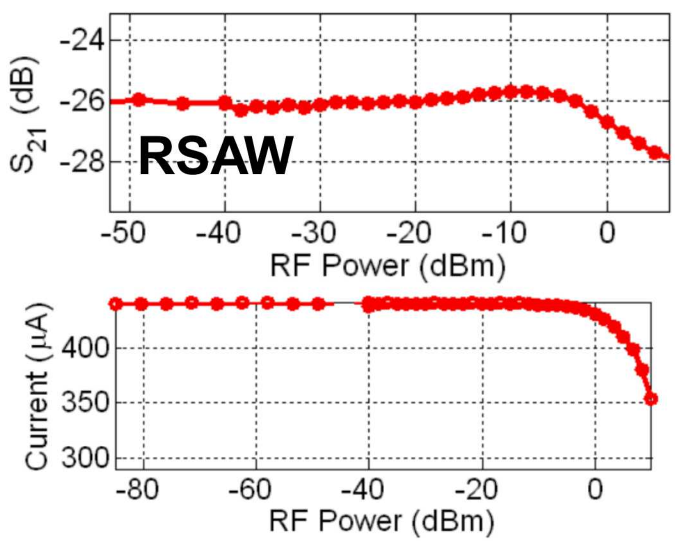
RSAW

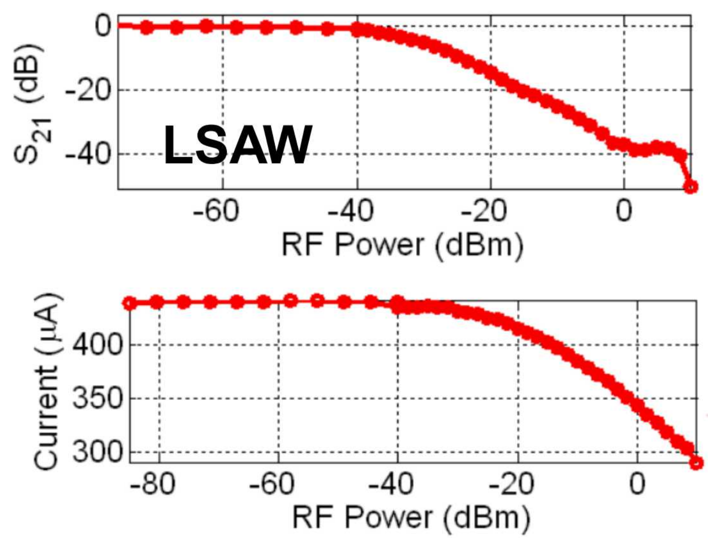


LSAW



- Gain and Current Saturation



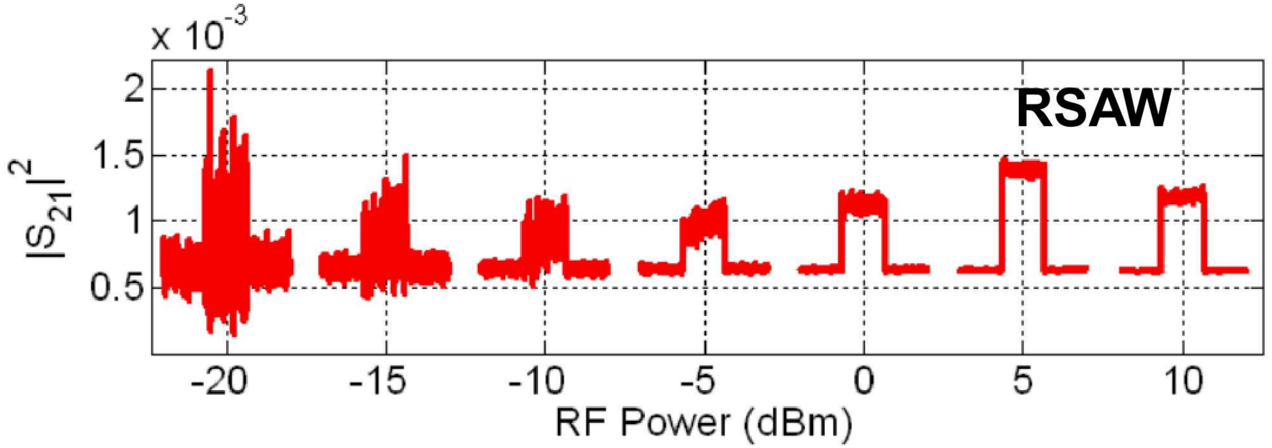


→ LSAW saturates at lower power and larger current impedance

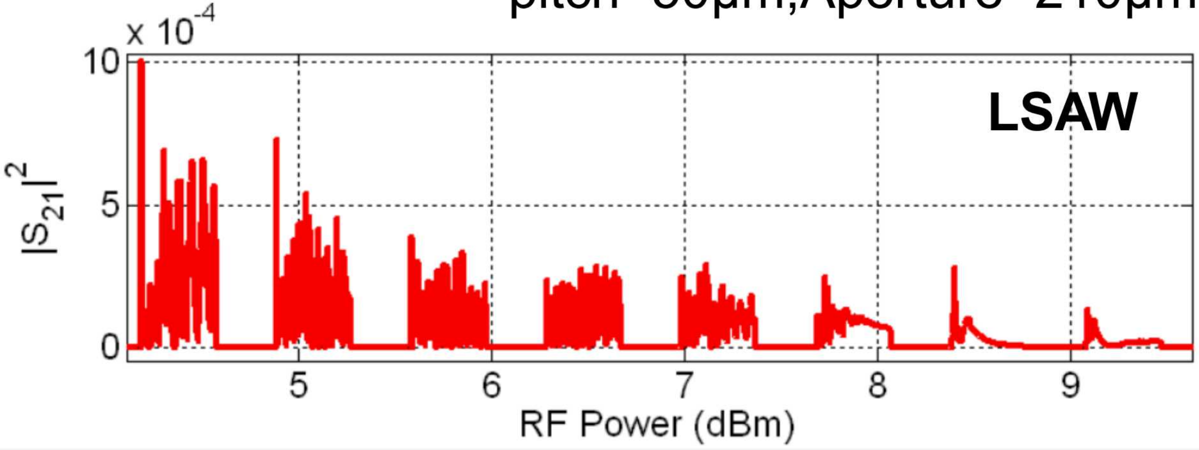
Sandia National Laboratories

Noise Competition In Gain Roll Off Region

- Gain in a short distance is sufficiently large that noise saturation effects come into play Noise saturation



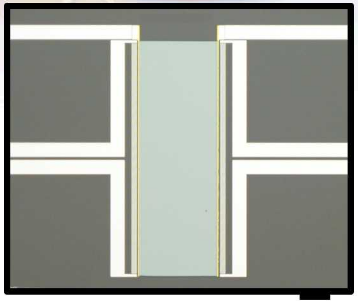
- Similar Device with: Amplifier: Length=1mm, Width=1μm, Transducer: $N_{fingers}$ =90, pitch=50μm,Aperture=210μm



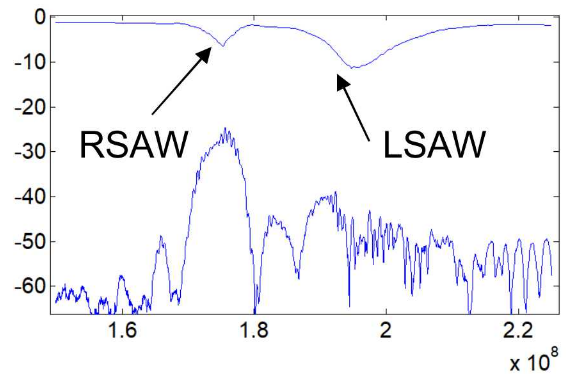
Sandia National Laboratories

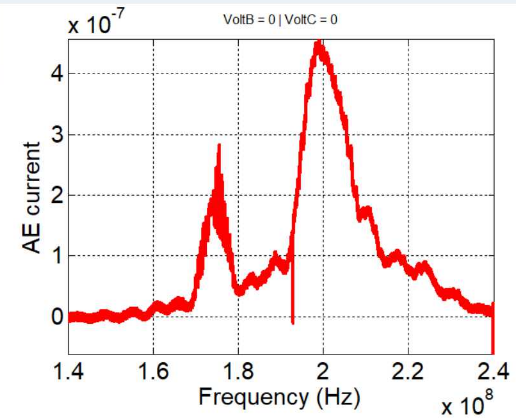
Best Performer LSAW

- Confirm KT2 by measuring AE current

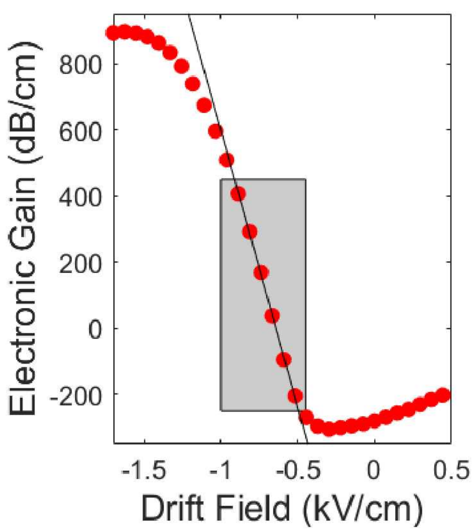


250 µm





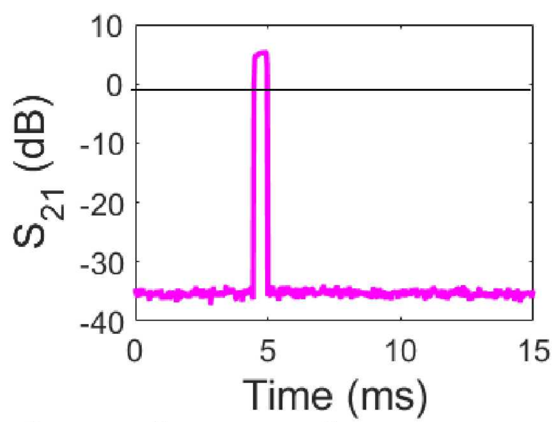
- We achieved large gain using LSAW:
  → 5dB terminal, 30dB electronic with 90mW power

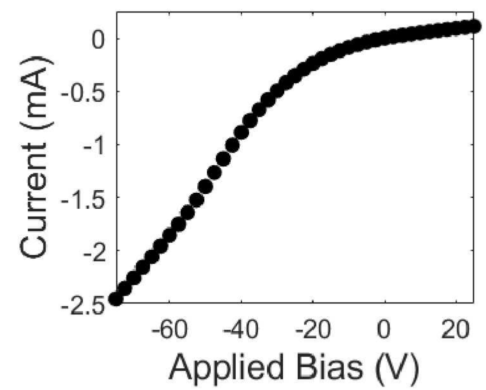


$$n_d = 5.2e15cm^{-3}$$

$$\mu = 732\text{cm}^2/\text{V}$$

L. Hackett, et. Al. “High-Gain Leaky Surface Acoustic Wave Amplifier in Epitaxial InGaAs on Lithium Niobate Heterostructure”. APL 2019





→ 41^o or 64^o cuts

→ Use Single-Phase unidirectional transducer design (SPUDT)

Sandia National Laboratories

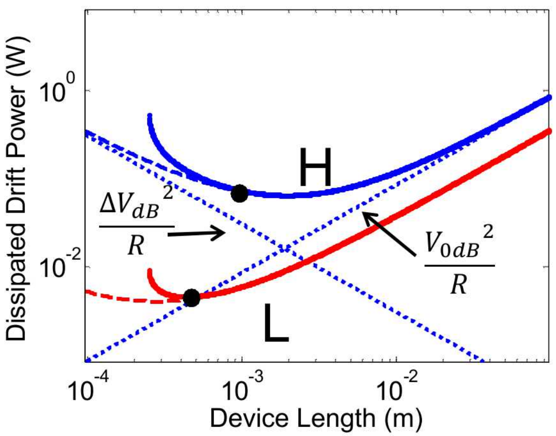
Power Optimization

- Trade off between long devices needing more power for 0dB and short devices burning up power with a fixed $\Delta \boldsymbol{V}_{\boldsymbol{dB}}$

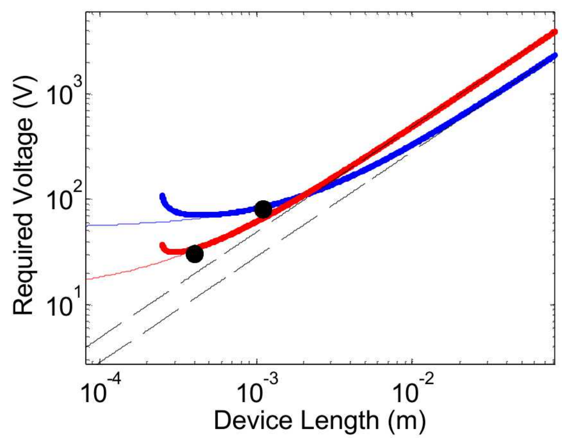
H $\quad \mathrm{n_d} = 20e15cm^{-3} \quad \mu = 1700\mathrm{cm}^2/\mathrm{V}$

L $\quad \mathrm{n_d} = 5.2e15cm^{-3} \quad \mu = 732\mathrm{cm}^2/\mathrm{V}$

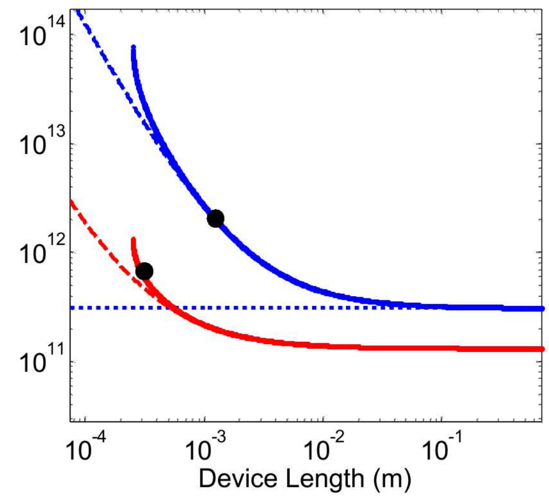
- Voltage required for 10 dB of gain



- Total Power dissipated



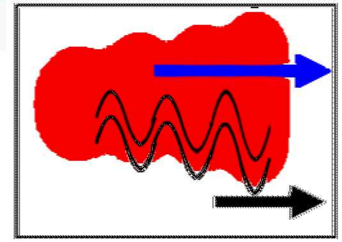
- Power Per unit volume



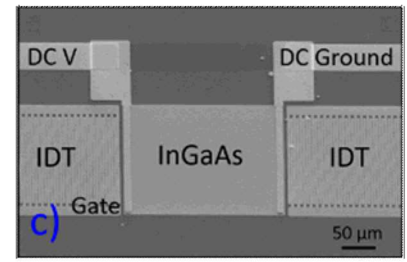
- Device Lengths are near optimal values
- Optimal dissipation is not the only consideration
  - Longer devices need more voltage
  - But dissipate less power per unit volume
  - Noise competition

Sandia National Laboratories

Conclusion



- Given overview of gain via AE interaction
- Proposed a scalable fabrication method based on wafer-scale bonding of InGaAs and Lithium Niobate



- Demonstration of strong gain interaction
  - Terminal gain with LSAW
- Next step steps:
  - 41^{o} or 64^{o} cuts
  - SPUDT
  - CW operation