晶圓世界篇_POI _怕熱的SAW

2. FoM, K^2, Q, Temperature Compensation and Spurious Modes

王不老說半导

晶圓世界篇_POI _怕熱的SAW

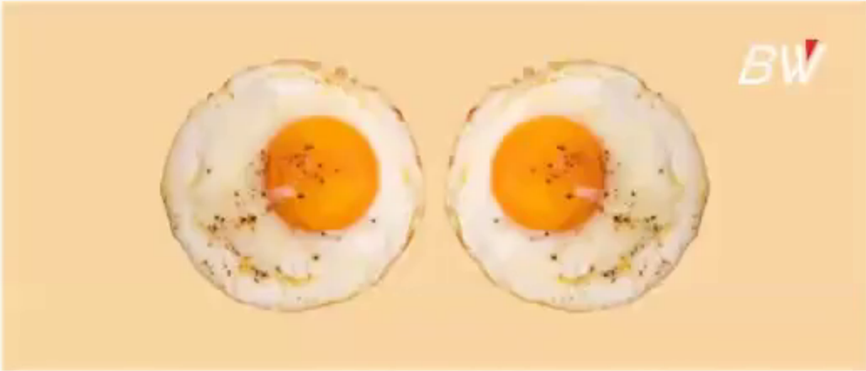
2. FoM, K^2, Q, Temperature Compensation and Spurious Modes

王不老說半导

制造精子需要高於還是低於体溫?

- 正常情况下，阴囊区的温度在33℃，比体温低4℃!这个温度是最适合睾丸的生长发育，也是“小蝌蚪”成长的最好的环境
- 睾丸被装在阴囊之中，且“孤悬海外”，很重要的原因就是可以让睾丸的温度低于身体的温度，这样睾丸才可以正常的工作
- 在POI世界裡，LT($LiTaO_3$)竟然也是如此，那麼我們如何幫助LT解決此問題?

愛穿緊身褲的後果很嚴重



http://baby.sina.com.cn/health/11/2604/2011-04-26/0835183098.shtml

回味: Pros and Cons of $LiTaO_3$

Table 1.1 Common surface-wave materials.

	Y–Z lithium niobate ($LiNbO_3$)	128°Y–X lithium niobate ($LiNbO_3$)	ST–X quartz (SiO_2)	36°Y–X lithium tantalate* ($LiTaO_3$)
v_f (m/s)	3488	3979	3159	4212
$\Delta v/v = k^2$	2.4%	2.7%	0.06%	2.4%
$\varepsilon_\infty/\varepsilon_0$	46	56	5.6	50
TCD (ppm/°C)	94	75	0	32
Advantage	Low diffraction, strong coupling	Low bulk waves, strong coupling	Small TCD	Strong coupling, moderate TCD
Disadvantage	Large TCD, strong bulk waves	Large TCD	Weak coupling	
Suitability	Wide-band filters, RACs, convolvers	Wide-band filters	Narrow-band filters, resonators, pulse compression	Low-loss filters, RF filters

RAC: reflective array compressor.
*Leaky wave, special considerations apply – see text.

Surface Acoustic Wave Filters, Second Edition With Applications to Electronic Communications and Signal Processing, David Morgan, 2007

FoM: 度量夫妻三觀的搭配程度

- 我們比較各SAW(或BAW)的优劣當然需要 FoM: 度量夫妻三觀的搭配程度 指標 = FoM (Figure-of-Merit)，其中自必包含最重要的成分，如與材質耦合程度(k^2)，以及與頻率f有相關的品質因素(Q)
  - FoM = $k^2 \times Q(f)$
- 图右顯示，天下沒有白吃的午餐，頻率越高，FoM越低
  - ∴ SAW > 4G，心有餘而力不足!

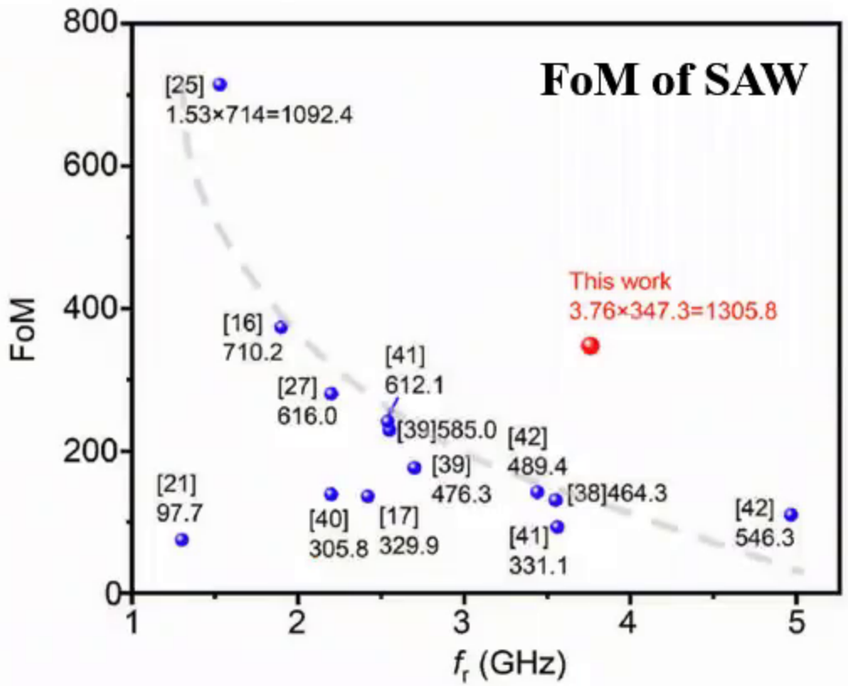


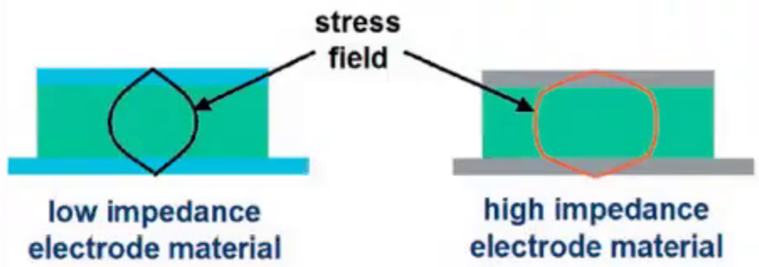
FIG. 4. A comparison of the reported SAW resonator with prior reports in terms of FoM and f_r.

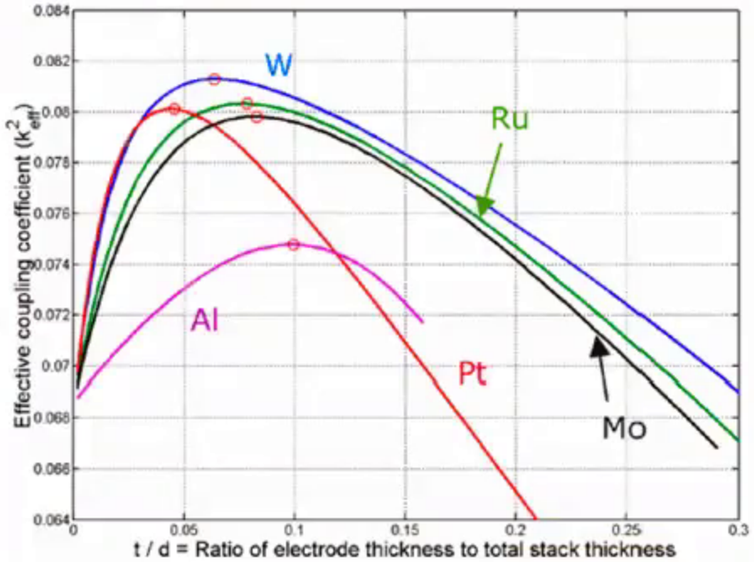
Over GHz bandwidth SAW filter based on 32 Y-X LN/SiO2/poly-Si/Si heterostructure with multilayer electrode modulation, Su et al, APL 120, 253501 (2022)

試問: 為何夫妻三觀第一觀(k^2)必有峰值?

解答: 蓋近之則逊,远之則不恭也

- 波太靠近Electrode/Piezo的介面，就看見介面很醜(所有人太近看，其實都醜)，遠距離戀愛，感受不到對方的濃情密意→ weak couplings
- ∴ a maximum for k^2 as the function of Electrode/Piezo thickness ratio



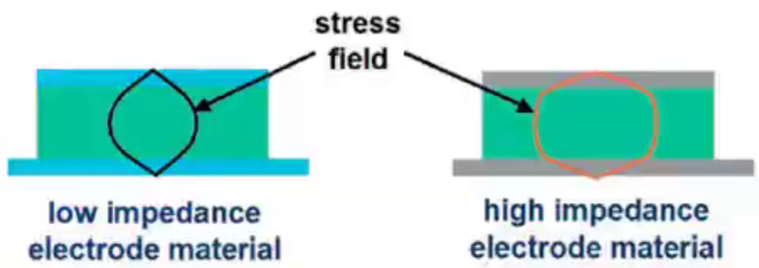


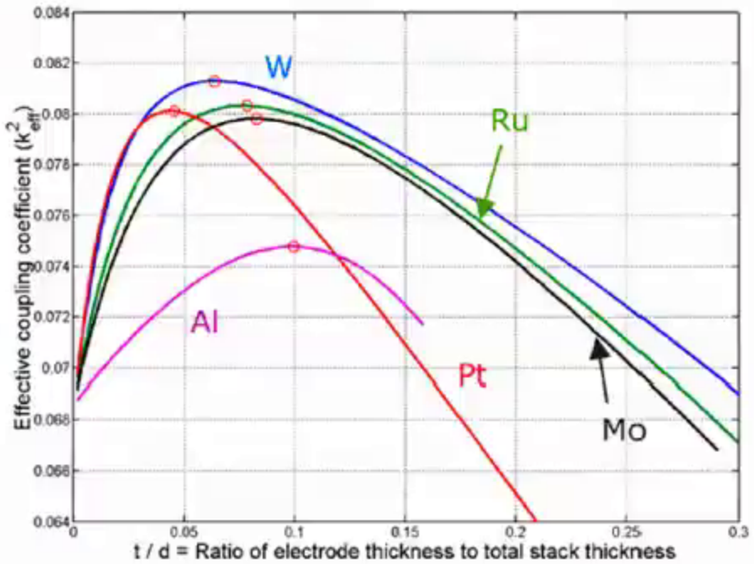
Liu et al, Materials, Design, and Characteristics of Bulk Acoustic Wave Resonator: A Review, *Micromachines* 2020, *11*, 630

試問: 為何夫妻三觀第一觀(k^2)必有峰值?

解答: 蓋近之則逊,远之則不恭也

- 波太靠近Electrode/Piezo的介面，就看見介面很醜(所有人太近看，其實都醜)，遠距離戀愛，感受不到對方的濃情密意→ weak couplings
- ∴ a maximum for k^2 as the function of Electrode/Piezo thickness ratio





Liu et al, Materials, Design, and Characteristics of Bulk Acoustic Wave Resonator: A Review, *Micromachines* 2020, *11*, 630

試問: 夫妻三觀第二觀(Q)又如何?

解答: Q指的是夫妻不停鬥嘴內耗之後，愛情仍然堅貞的程度

- Q factor = stored energy (愛情) / power dissipated of one cycle (耗損).
  - Loss high → lower Q and *rounding of the filter corners* (方形波竟然稜角变圓了，有如帥哥變胖，當然難調窄波了，bad for narrowband modulations)
- 就波而言，有許多所謂的耗損机制(loss mechanisms)，例如acoustic losses (laterally leaking waves, reflector loss，波被四處介面反彈的漏損), ohmic losses of the electrodes (eddy current，一種由电极彼此不協調而產生的漏電流, 有所謂I^2R loss) and viscoelastic losses (hysteresis and energy loss，好似橡膠被壓縮再彈回，仍有能量損耗的)

Liu et al, Materials, Design, and Characteristics of Bulk Acoustic Wave Resonator: A Review, *Micromachines* 2020, *11*, 630

試問: 夫妻三觀第二觀(Q)又如何?

解答: Q指的是夫妻不停鬥嘴內耗之後，愛情仍然堅貞的程度

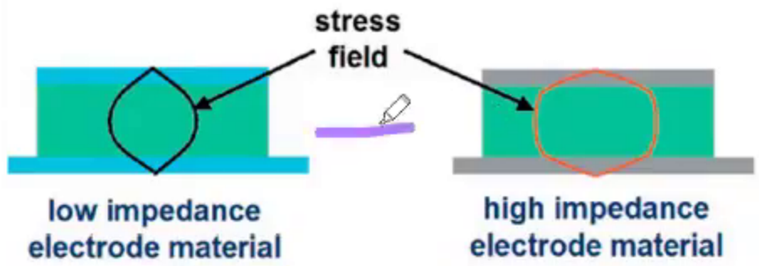
- Q factor = stored energy (愛情) / power dissipated of one cycle (耗損).
  - Loss high → lower Q and *rounding of the filter corners* (方形波竟然稜角变圓了，有如帥哥變胖，當然難調窄波了，bad for narrowband modulations)
- 就波而言，有許多所謂的耗損机制(loss mechanisms)，例如acoustic losses (laterally leaking waves, reflector loss，波被四處介面反彈的漏損), ohmic losses of the electrodes (eddy current，一種由电极彼此不協調而產生的漏電流, 有所謂I^2R loss) and viscoelastic losses (hysteresis and energy loss，好似橡膠被壓縮再彈回，仍有能量損耗的)

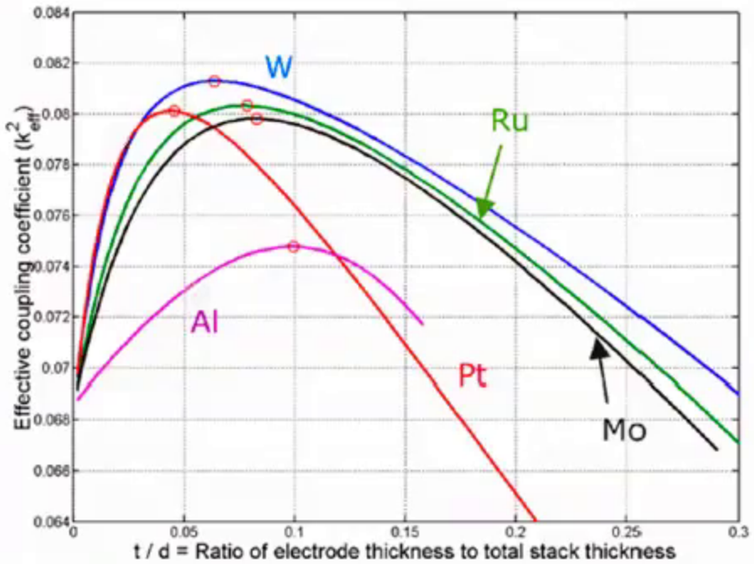
Liu et al, Materials, Design, and Characteristics of Bulk Acoustic Wave Resonator: A Review, *Micromachines* 2020, *11*, 630

試問: 為何夫妻三觀第一觀(k^2)必有峰值?

解答: 蓋近之則逊,远之則不恭也

- 波太靠近Electrode/Piezo的介面，就看見介面很醜(所有人太近看，其實都醜)，遠距離戀愛，感受不到對方的濃情密意→ weak couplings
- ∴ a maximum for k^2 as the function of Electrode/Piezo thickness ratio





Liu et al, Materials, Design, and Characteristics of Bulk Acoustic Wave Resonator: A Review, *Micromachines* 2020, *11*, 630

試問: 夫妻三觀第二觀(Q)又如何?

解答: Q指的是夫妻不停鬥嘴內耗之後，愛情仍然堅貞的程度

- Q factor = stored energy (愛情) / power dissipated of one cycle (耗損).
  - Loss high → lower Q and *rounding of the filter corners* (方形波竟然稜角变圓了，有如帥哥變胖，當然難調窄波了，bad for narrowband modulations)
- 就波而言，有許多所謂的耗損机制(loss mechanisms)，例如acoustic losses (laterally leaking waves, reflector loss，波被四處介面反彈的漏損), ohmic losses of the electrodes (eddy current，一種由电极彼此不協調而產生的漏電流, 有所謂I^2R loss) and viscoelastic losses (hysteresis and energy loss，好似橡膠被壓縮再彈回，仍有能量損耗的)

Liu et al, Materials, Design, and Characteristics of Bulk Acoustic Wave Resonator: A Review, *Micromachines* 2020, *11*, 630

試問: 夫妻三觀第二觀(Q)又如何?

- 解答: Q值就resonator所使用材質而言，相差甚大(如右图表所示)
- 一般就產品而言，Q值 > 2000 為佳
- 就BAW而言，电極材料也有巨大影响(見下頁)

$$Q_{s,p} = \frac{f_{s,p}}{\Delta f_{s,p-3\,\mathrm{dB}}}$$

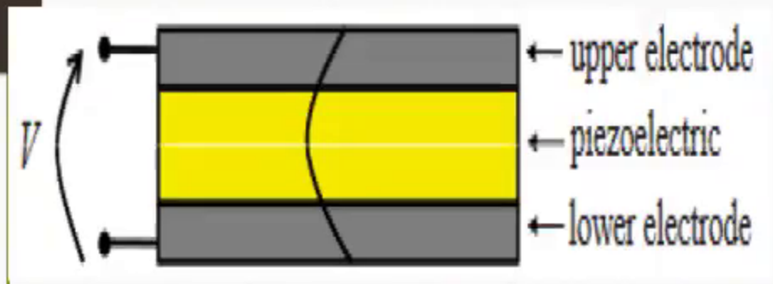
COMPARISON WORKS ON PERFORMANCE OF RESONATORS

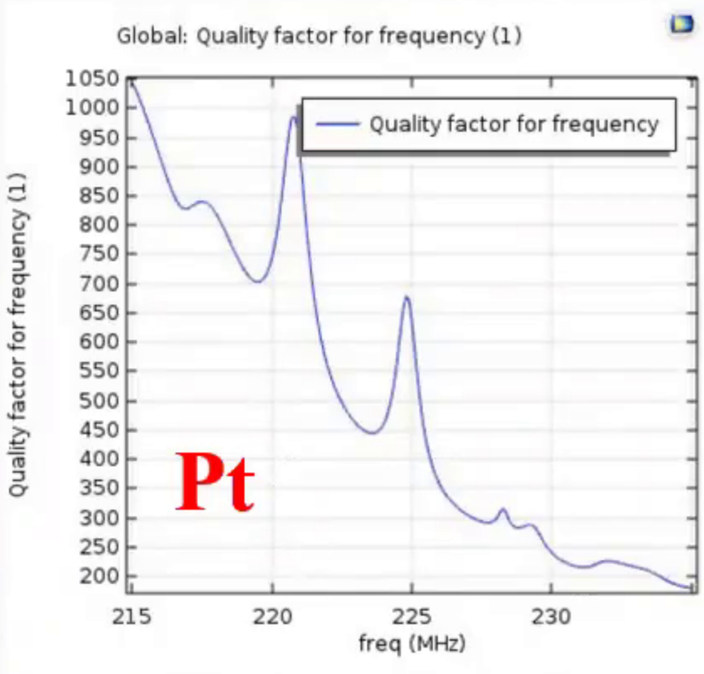
Materials	*f (MHz)*	*Q*
AlN/Al_2O_3[31]	*703.56*	*1347*
AlN/Al_2O_3[31]	*688.75*	*1082*
$Sc_{0.23}Al_{0.77}N/Al_2O_3$[9]	*1910*	*659*
$Sc_{0.27}Al_{0.73}N/Si$[32]	*295*	*100*
Sc(11.8%)AlN/Si[10]	*3648*	*146*
Lithium niobate substrate[33]	*2454.2*	*5125*
AlN/Sapphire[34]	*456*	*8140*
X-112°Y $LiTaO_3$ substrate[35]	*825*	*12000*
ST-cut quartz[36]	*434*	*8000-9800*
Crystal substrate made of quartz[37]	*433.9*	*13439*
$Sc_{0.2}Al_{0.8}N/AlN/Si$ (This work)	*f_s:447.13* *f_p:447.50*	*Q_s:1313* *Q_p:7200*

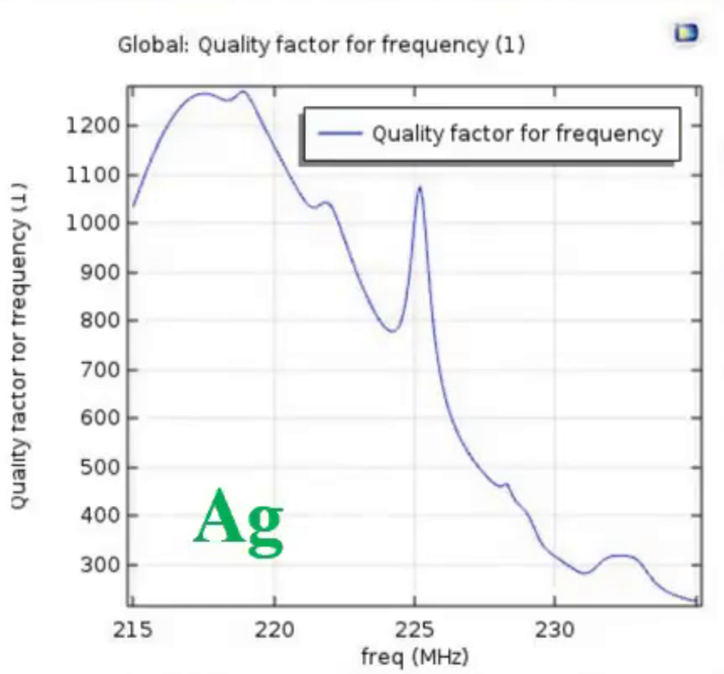
A High Q Value ScAlN/AlN-Based SAW Resonator for Load Sensing, Lin et al, TED, 68(10), 2021, p.5192-5196

試問: 白金與銀电極，何者Q值較高?

解答: 就左下BAW結構而言，銀电極之Q值～220 MHz明顯較佳，



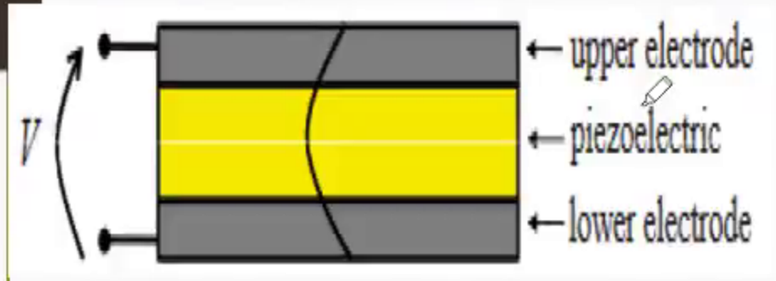


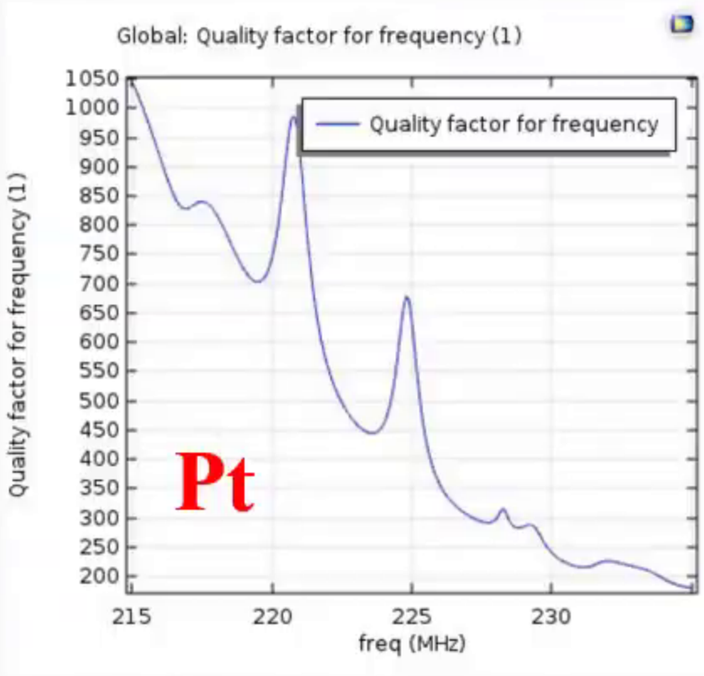


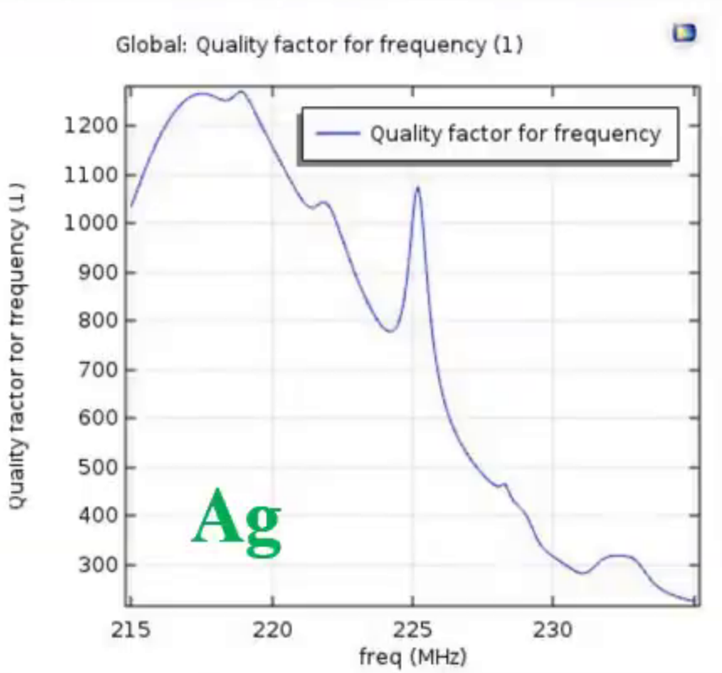
Q factor Enhancement of BAW Resonator using Electrode Optimization, Gayathri et al, ICOEI 2018, p.1298-1302

試問: 白金與銀电極，何者Q值較高?

解答: 就左下BAW結構而言，銀电極之Q值～220 MHz明顯較佳，



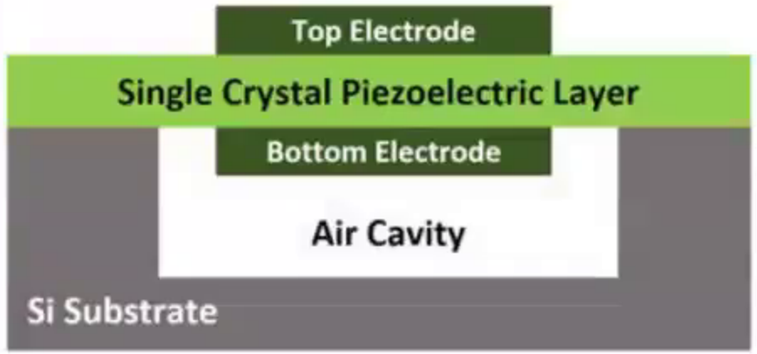


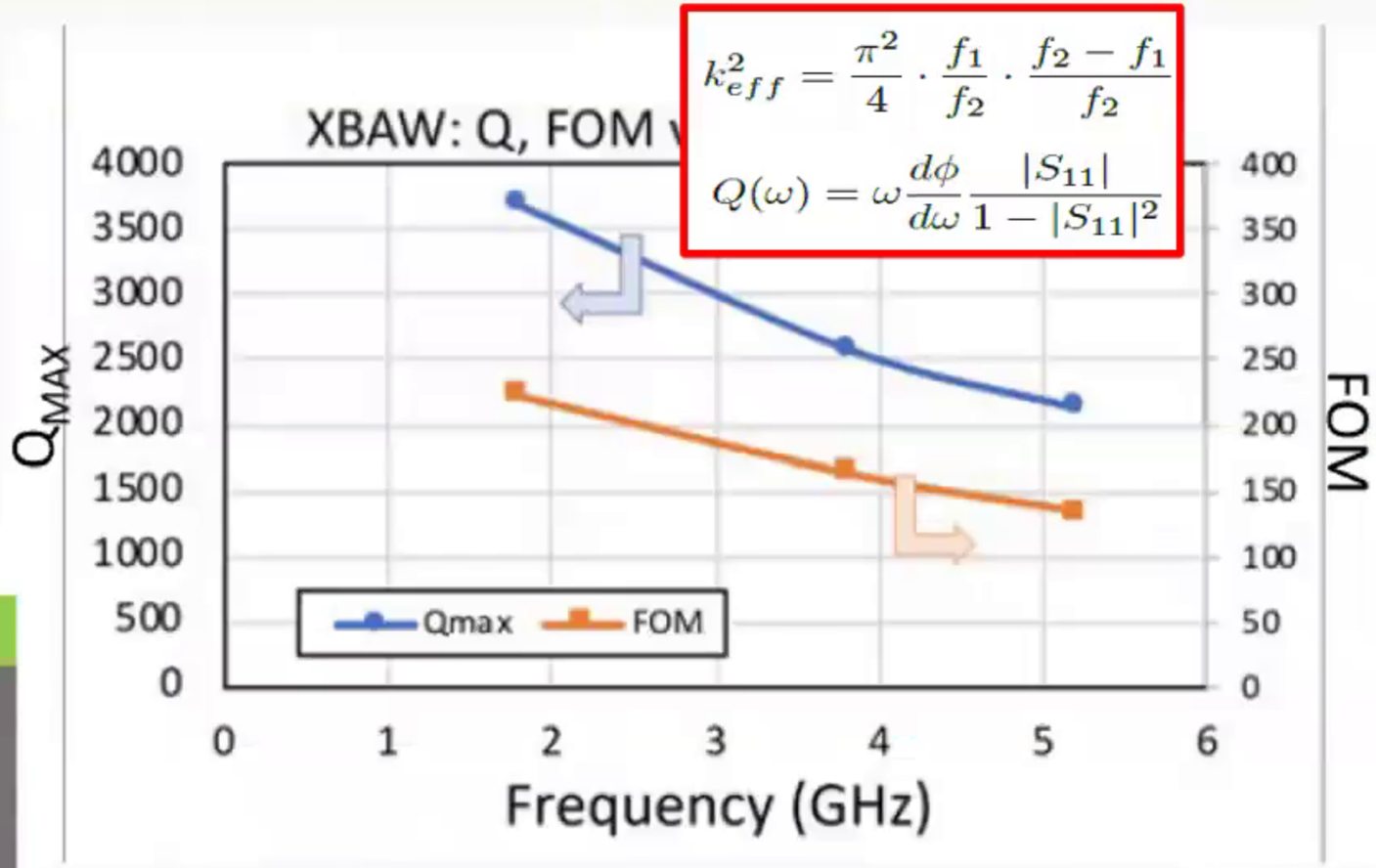


Q factor Enhancement of BAW Resonator using Electrode Optimization, Gayathri et al, ICOEI 2018, p.1298-1302

試問: 夫妻三觀第二觀(Q)又如何?

- 解答: 各家挖空心思，改变器件結構(如下图)，就想要在高頻區，能有高Q值，高FoM (如右图)

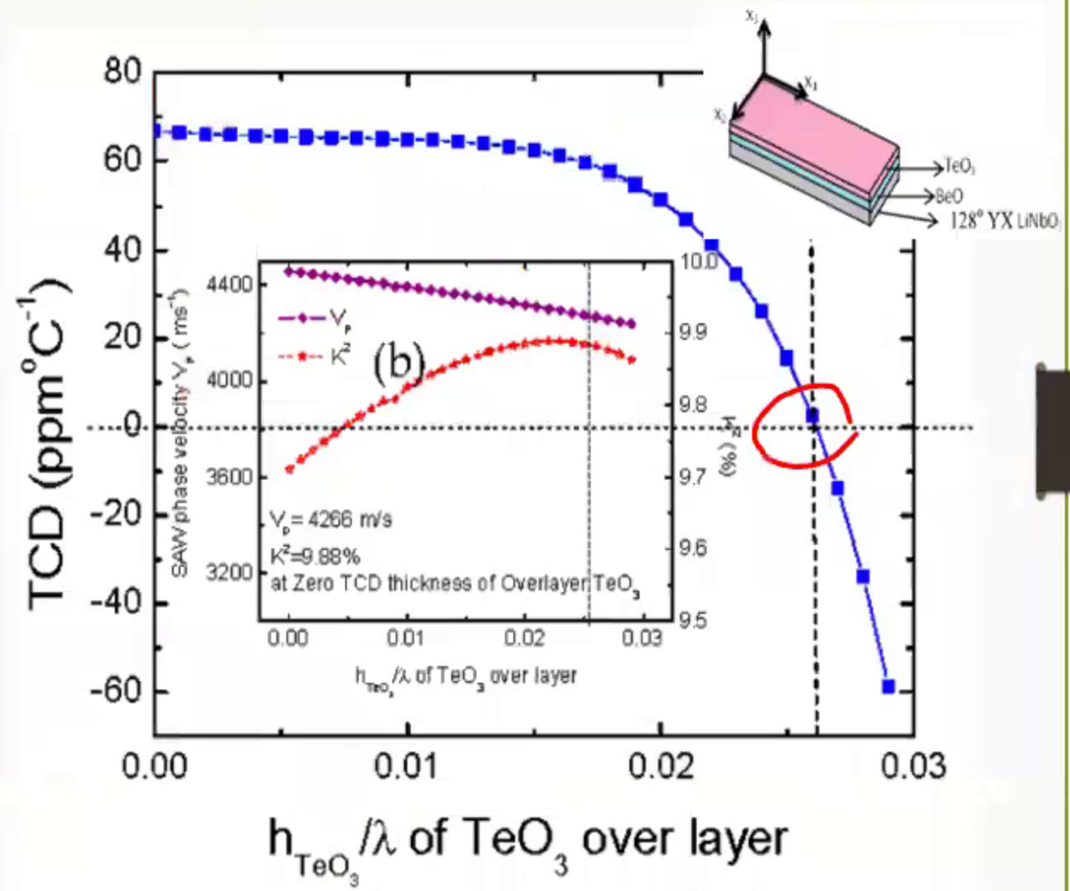




Vetury et al, "High Power, Wideband Single Crystal XBAW Technology for sub-6 GHz Micro RF Filter Applications," IUS 2018, pp. 206-212,

回味:Key Metrics for Piezoelectric: TCD

- **Q**: Why larger k^2 has a worse TCD?
- **A**: b/c the more you love someone, the more vulnerable you are 😜
  - Larger k^2 (coupling) also means more sensitive to temperature variation (∵ volume change)
- The temperature coefficient of delay (TCD ∝ TEC) is a big headache, but it can be tamed (to zero as in TeO_3/BeO(0.08λ)/$LiNbO_3$ SAW)

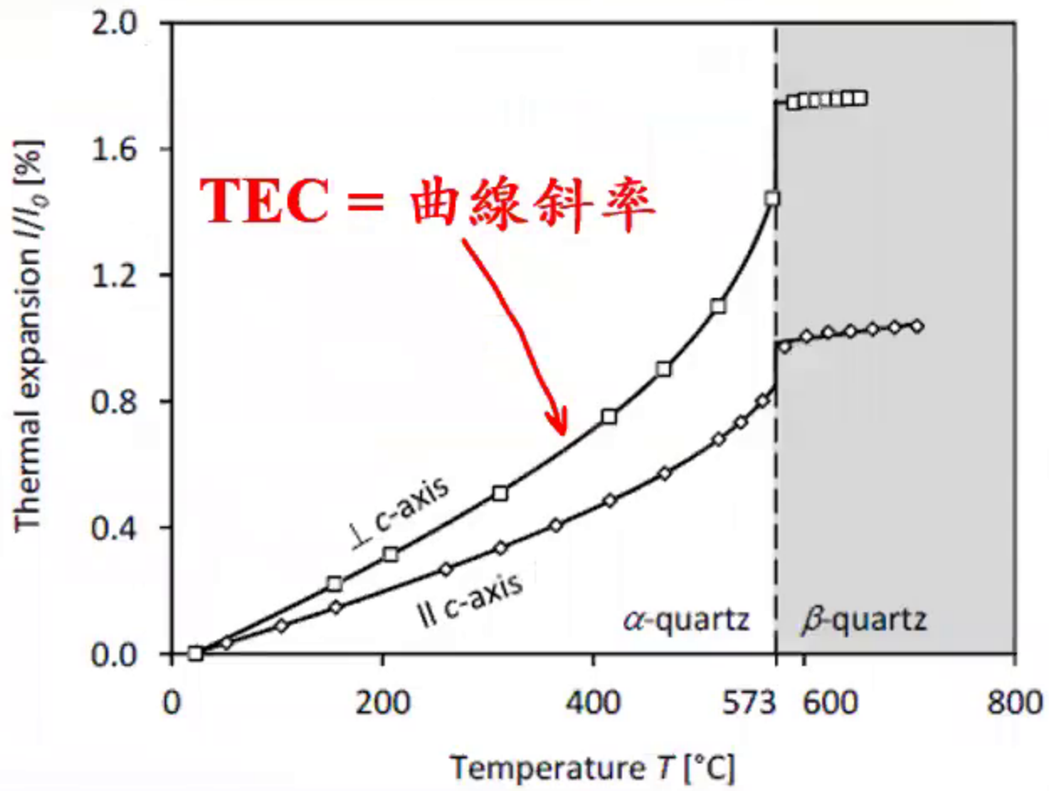


Enhanced Properties of SAW Device Based on Beryllium Oxide Thin Films, Soni et al, *Crystals* 2021, *11*(4), 332

試問: Piezo TCD太高又怎麼办?

解答: 以SiO_2補強

- LT/LN ($LiTaO_3$/$LiNbO_3$) 溫度越高越軟，然而SiO_2卻溫度越高越硬→ TCD ~ 0
- 又右图顯示，α-quartz体積隨溫度上升只有少量增加，而β-quartz幾乎不变
  - TEC($LiTaO_3$) = 18.3 ppm/K
  - TEC(SiO_2) = 0.5 ppm/K
  - TEC(Si) = 2.7 ppm/K
- 半导世界裡，石英(quartz)也因此被用來作為光罩的載体(見下一頁的插播)

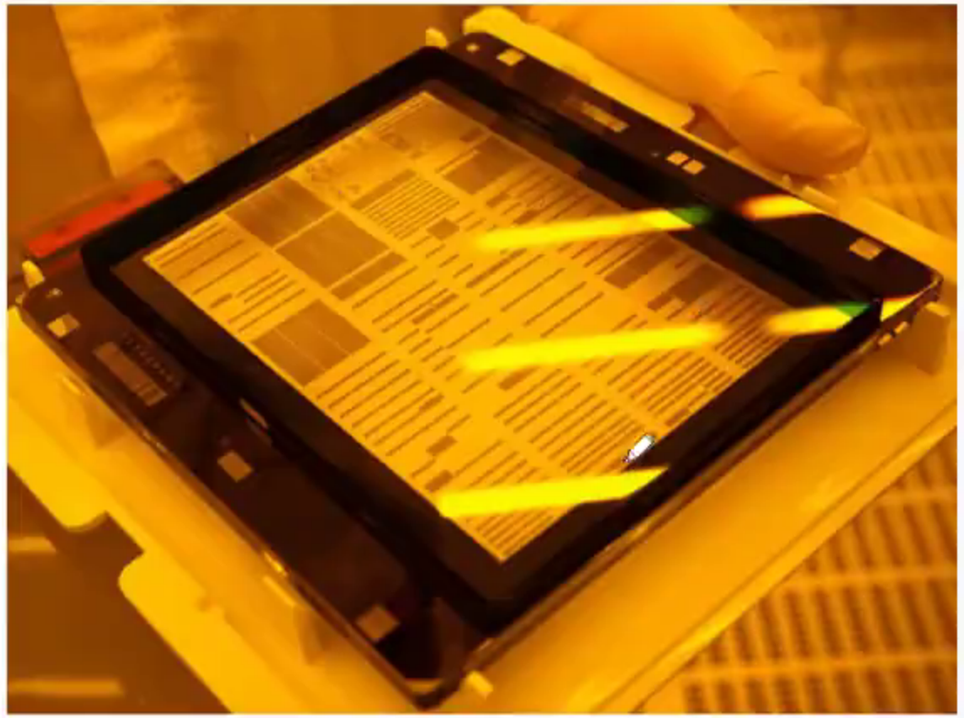


Surface energy engineering for LiTaO3 and α-quartz SiO2 for low temperature (<220 C) wafer bonding, Baker et al, JVCT A 37, 041101 (2019);

Elasticity and Viscoelasticity of Solid SiO2 as a Function of Frequency and Temperature， M. Sc. Geol. Steffen Klumbach, thesis, 2015

插播:石英為半导光罩的衬底

- 石英不只因為其透明，而且因為TEC小，故被用來作為半导光罩的衬底(substrate，如右)，以此避免光罩上的chrome pattern因溫度升高而变形太多



No.2 Photomask (PAM180904-MASKW)

i. Dimension(WxHxThickness): Square 5″ x 5″ x .090″

ii. Substrate: Quartz

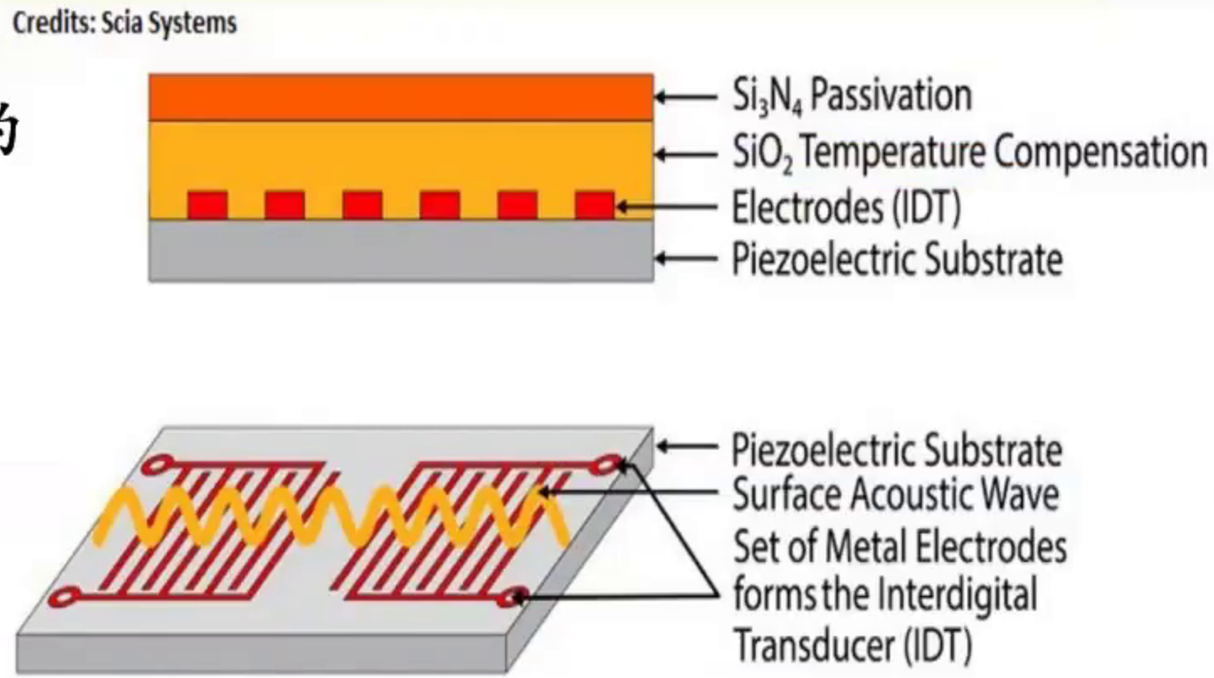
iii. Coating: Antireflective Chrome

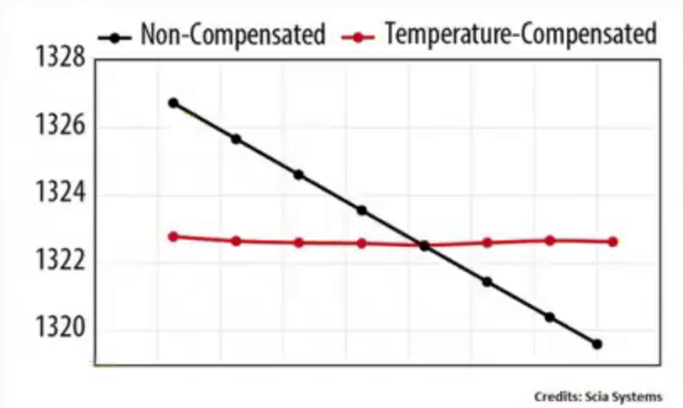
iv. Minimum feature /Critical Dimension (CD): 1 um+/-0.1 um

://www.powerwaywafer.com/chrome-photomask.html

天賜石英為良配: TC-SAW以SiO_2補強

- 在TC-SAW濾波器中，使用二氧化硅(SiO_2)薄膜来获得良好的频率温度補償系数(TCF)
  - TC = temperature-compensated
- 如下图紅線所示，目前已經可以做到一條直線了





https://www.everythingrf.com/community/what-is-tc-saw#:~:text=TC%2DSAW%20or%20Temperature%20Compensated,considerably%20by%20variations%20in%20temperature.

小結論: RF Filter SAW to BAW/BAR

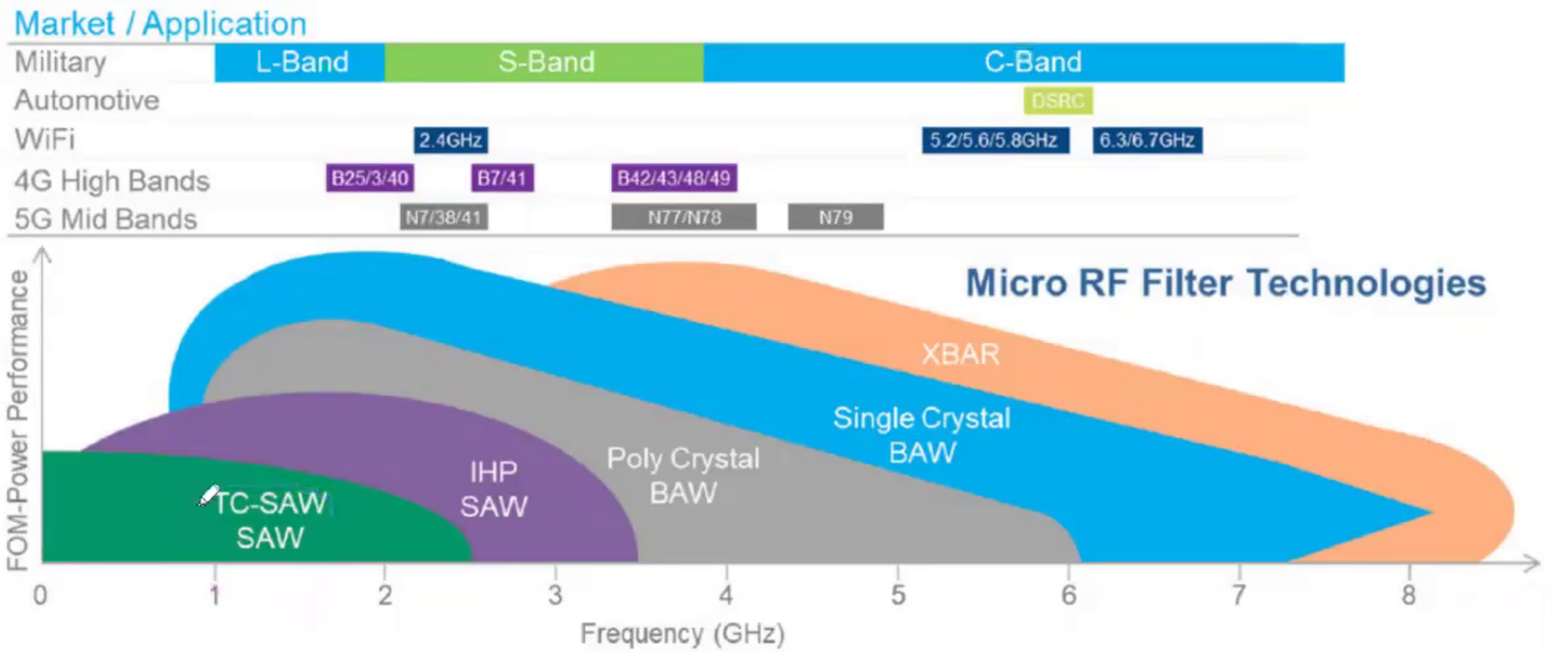
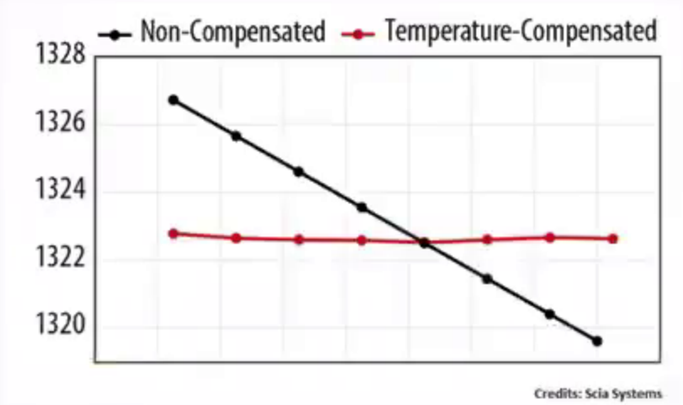


Figure 1. Market Application and Frequency Band Allocation of RF Filtering Technology [2].

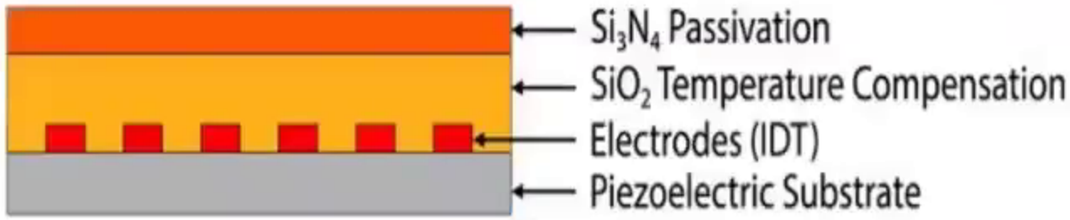
Materials, Design, and Characteristics of Bulk Acoustic Wave Resonator: A Review, Liu et al, Micromachines (Basel). 2020 July 11(7): 630.

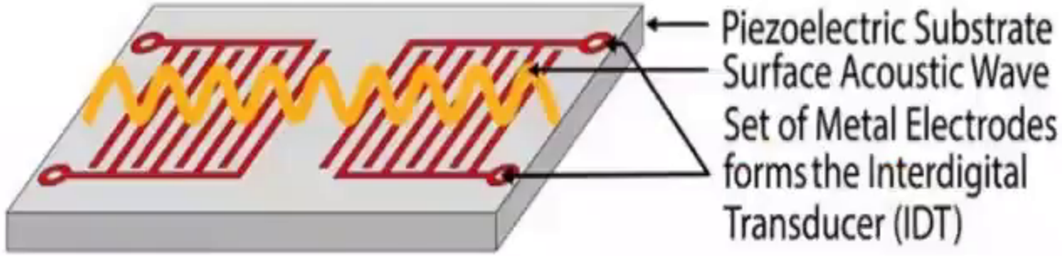
天賜石英為良配: TC-SAW以SiO_2補強

- 在TC-SAW濾波器中，使用二氧化硅(SiO_2)薄膜来获得良好的频率温度補償系数(TCF)
  - TC = temperature-compensated
- 如下图紅線所示，目前已經可以做到一條直線了



Credits: Scia Systems

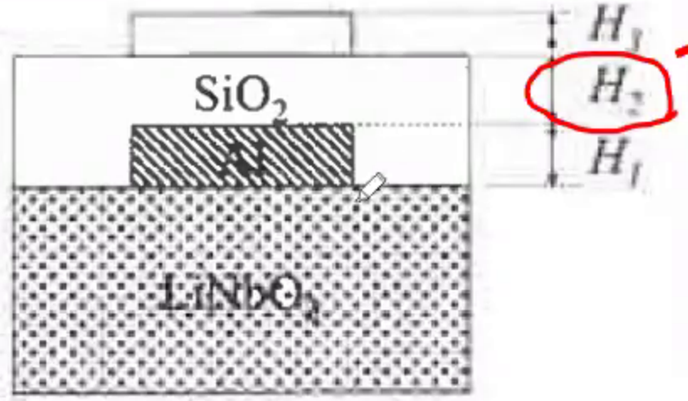


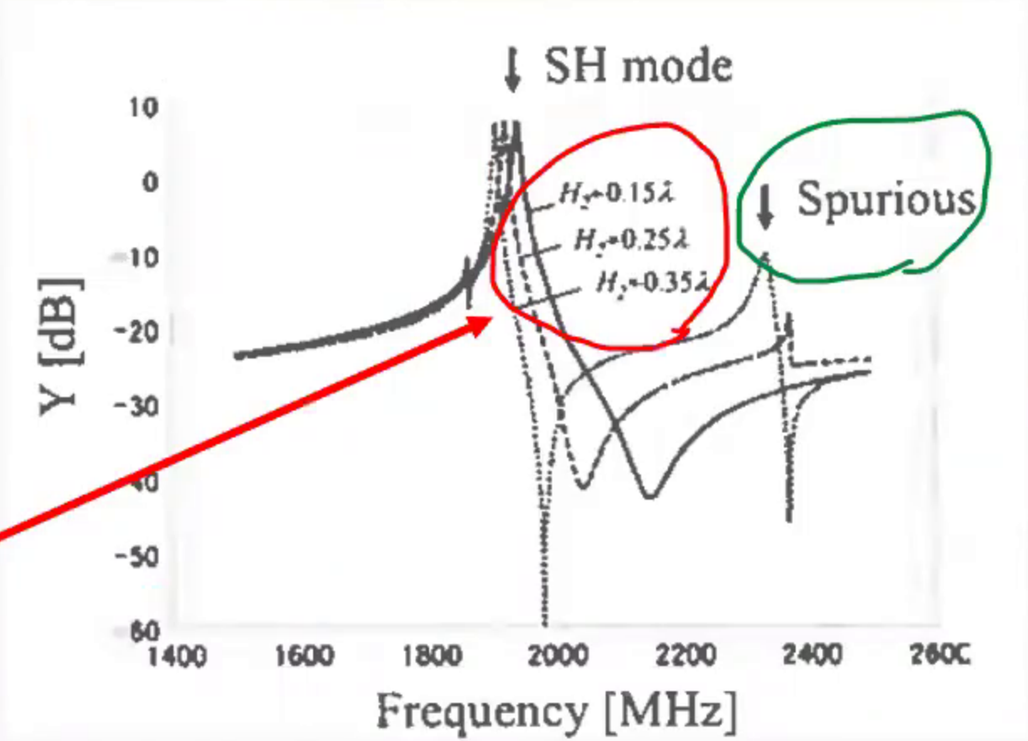


https://www.everythingrf.com/community/what-is-tc-saw#:~:text=TC%2DSAW%20or%20Temperature%20Compensated,considerably%20by%20variations%20in%20temperature.

天賜良配(TC-SAW+SiO_2)的优化

- 滤波器性能很大程度上，當然取决于沉积SiO_2的质量
- 对于窄带应用，增加SiO_2厚度(如图中的H2)能实现良好的TCF特性，也能减少雜訊(spurious modes)

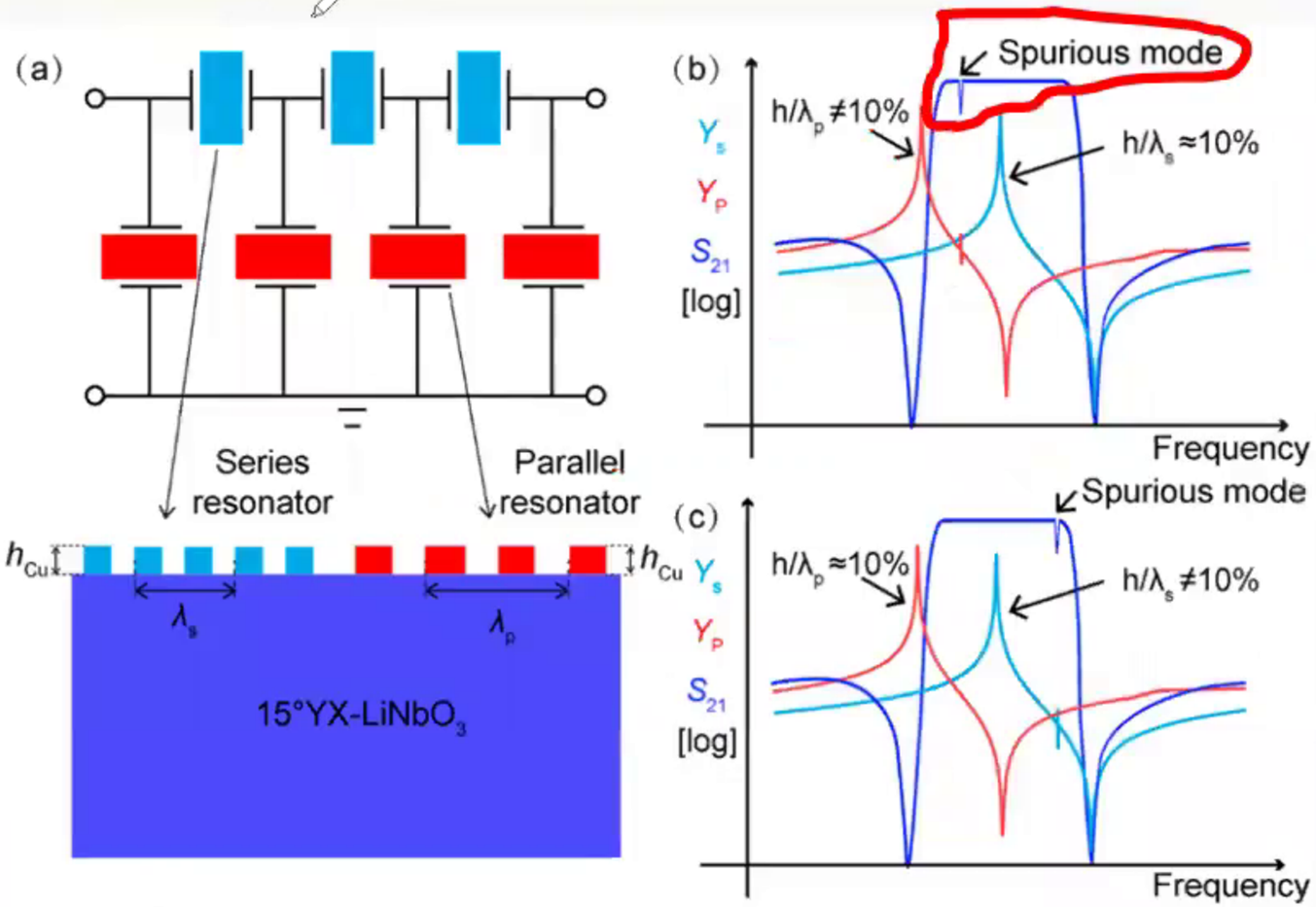




https://cdn.everythingrf.com/live/Chiba_Symposium_112015_637413678814754864.pdf

RF Filter的惡客: Spurious Modes

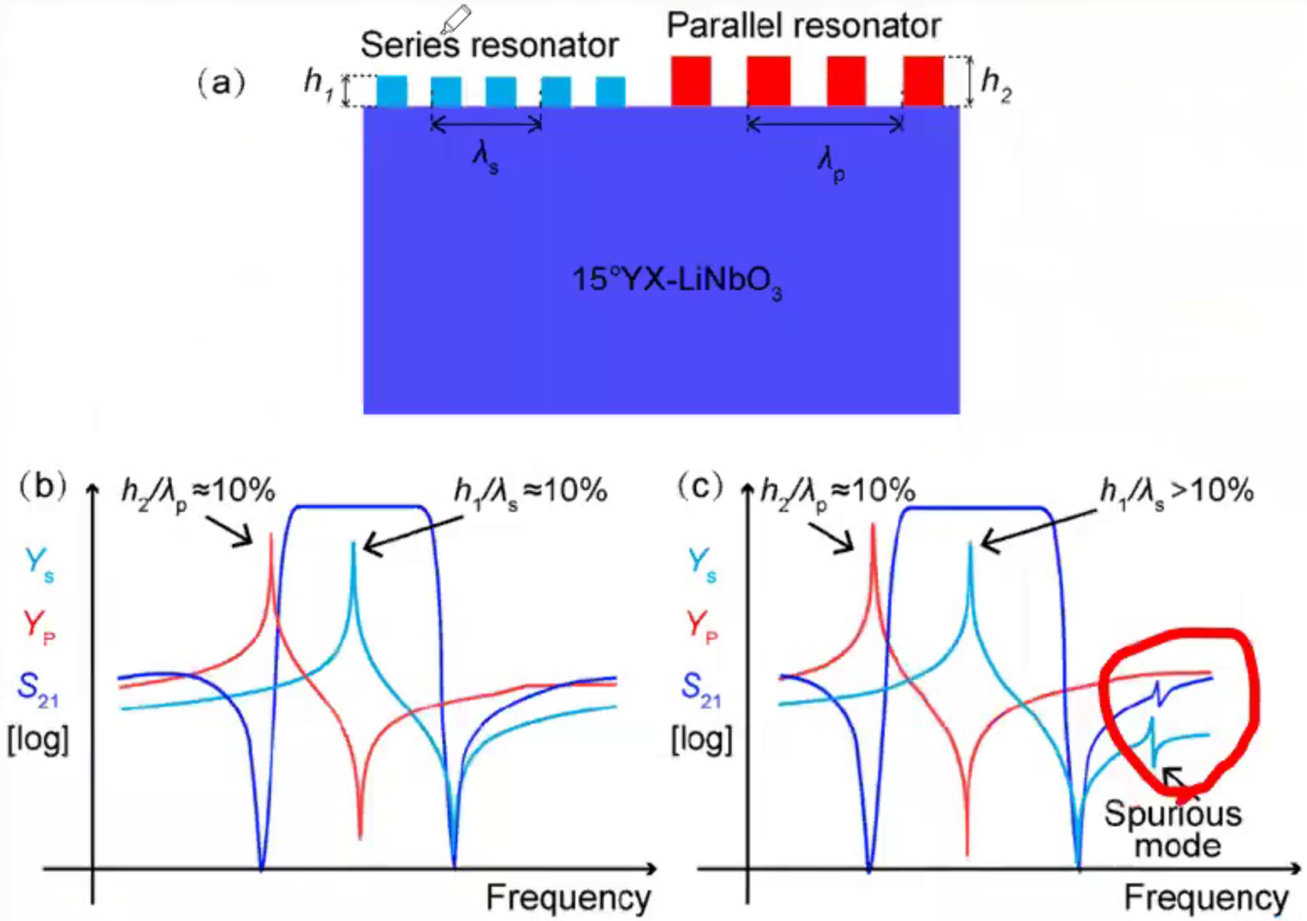
- 动态范围超过30 dB的SAW器件，很討厭的插隊惡客＝杂散(Spurious modes)
- 如右图所示，这些乃不請自來的惡客，對器件品質有巨大影响
- 人人欲去之而後快



Fractional Bandwidth up to 24% and Spurious Free SAW Filters on Bulk 15°YX-LiNbO3 Substrates Using Thickness-Modulated IDT Structures, Lu et al, Micromachines 2022, 13, 439

驅除惡客有時並不難

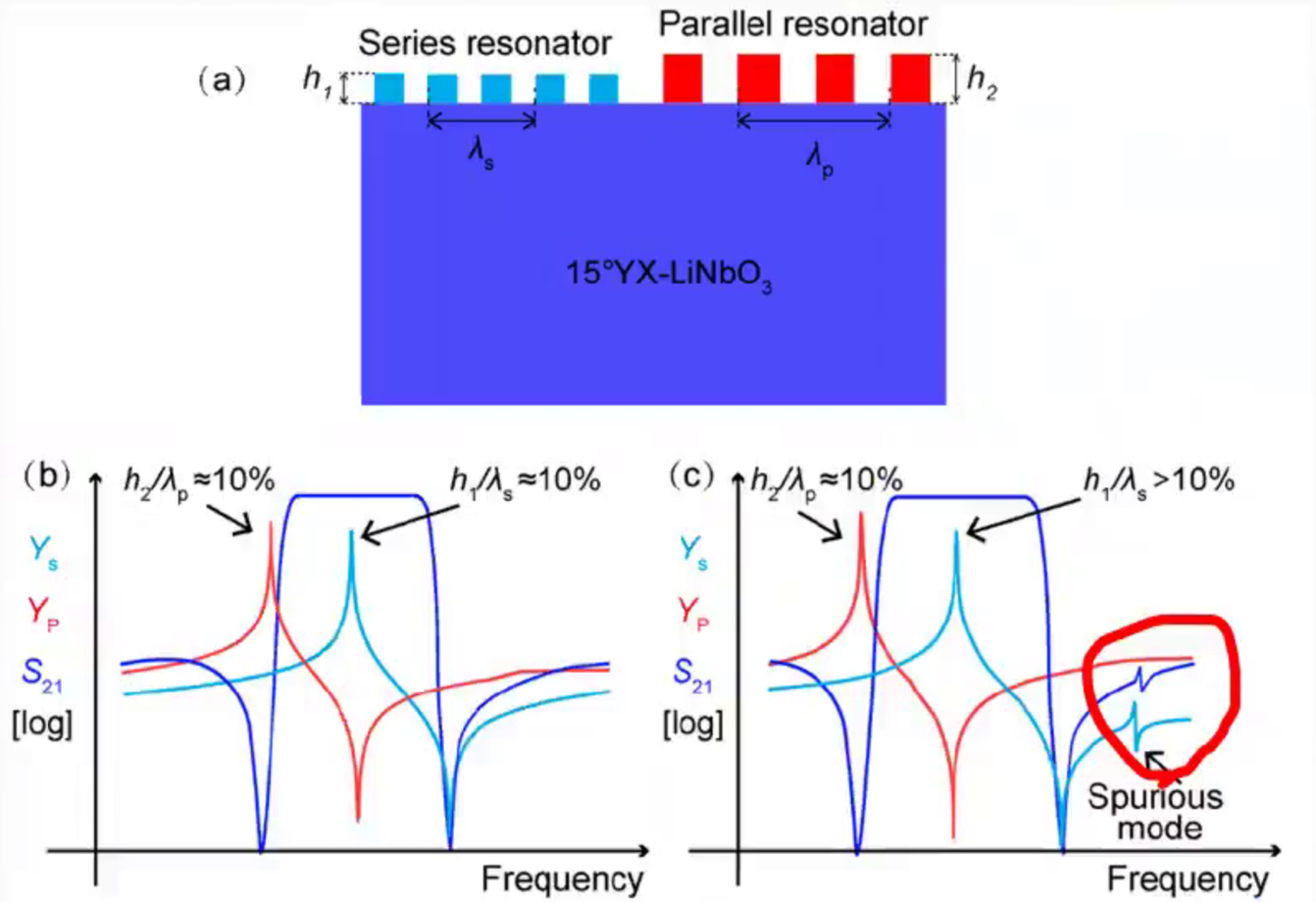
- 有最近研究(Lu, 2022)指出，改變电極厚度(如右图中的H_1/H_2，竟能輕易移動spurious mode的頻率位置)



Fractional Bandwidth up to 24% and Spurious Free SAW Filters on Bulk 15°YX-LiNbO3 Substrates Using Thickness-Modulated IDT Structures, Lu et al, Micromachines 2022, 13, 439

驅除惡客有時並不難

- 有最近研究(Lu, 2022)指出，改變电極厚度(如右图中的H_1/H_2，竟能輕易移動spurious mode的頻率位置)



Fractional Bandwidth up to 24% and Spurious Free SAW Filters on Bulk 15°YX-LiNbO3 Substrates Using Thickness-Modulated IDT Structures, Lu et al, Micromachines 2022, 13, 439

驅除惡客有時並不難

- **Yandrapalli 以挖空背面硅(backside etching of Si)制程美容，乾脆將不良醜陋介面除去，spurious mode惡客也因之大幅減少**
  - 只剩下S0(右下图)
- 當然成本也增加了

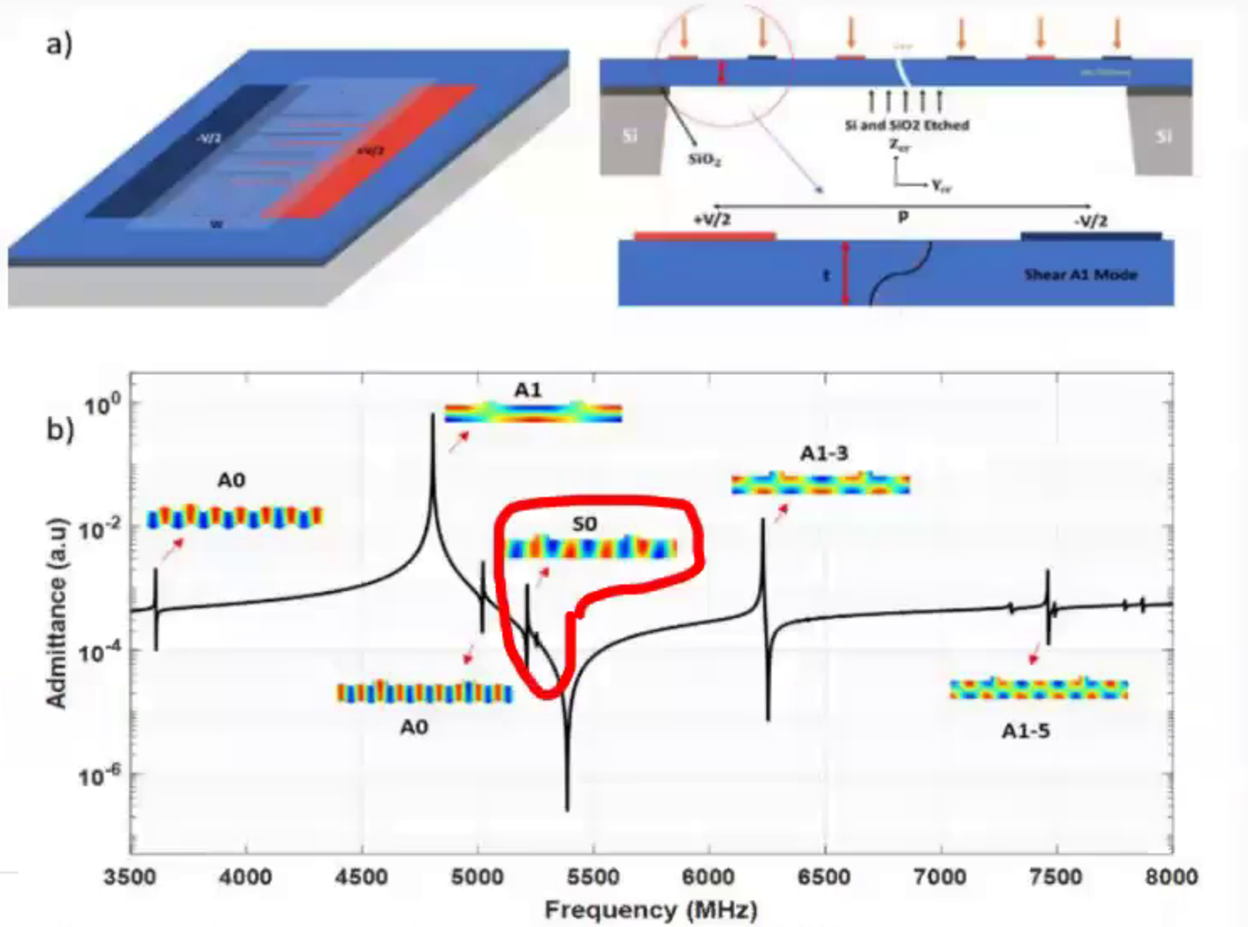
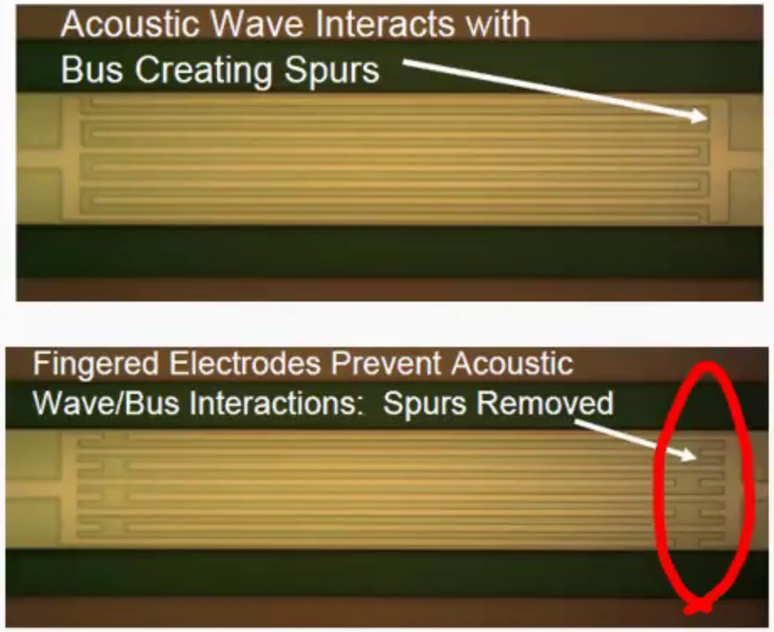


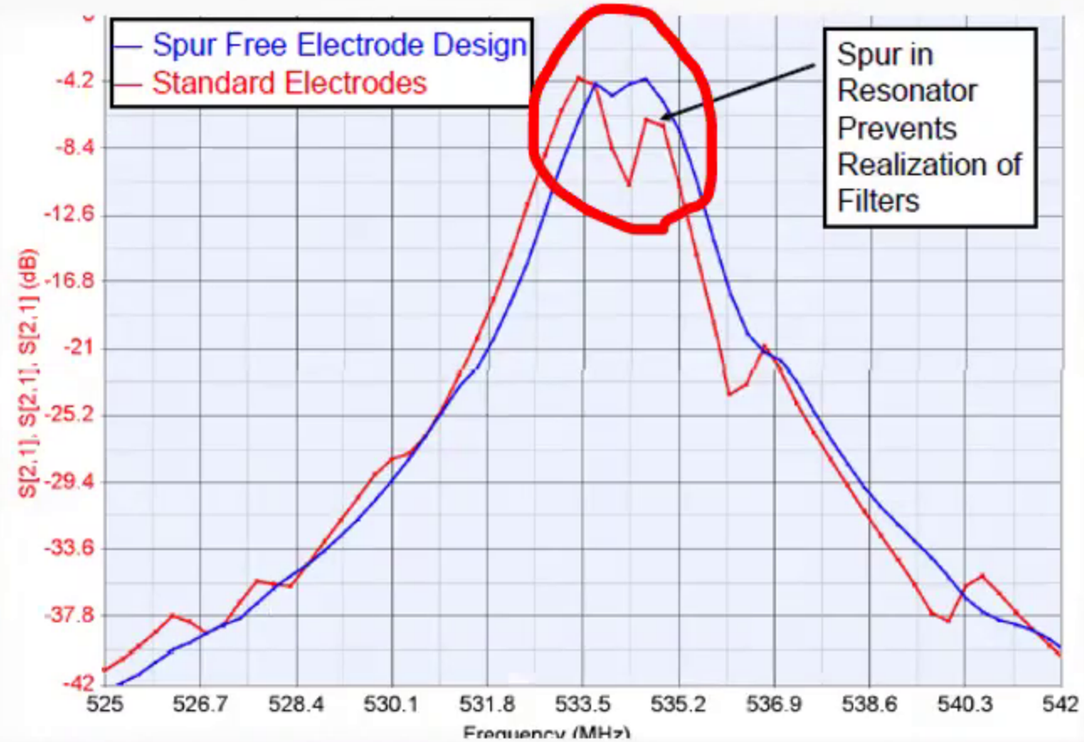
Fig. 1. a) Schematic of XBAR with suspended Lithium Niboate membrane and Alumnium electrodes on top obtained from backside etching of Si and

Analysis of XBAR resonance and higher order spurious modes
Yandrapalli et al, IUS, 2019, pp. 185-188,

驅除惡客有時並不難

- Olsson优化了器件尾端設計 (by adding an extra ½ λ section)，竟可將惡客驅除，也是厲害





Olsson et al, "Origins and mitigation of spurious modes in aluminum nitride microresonators," IUS 2010, pp. 1272-1276

小結論: RF Filter SAW to BAW/BAR

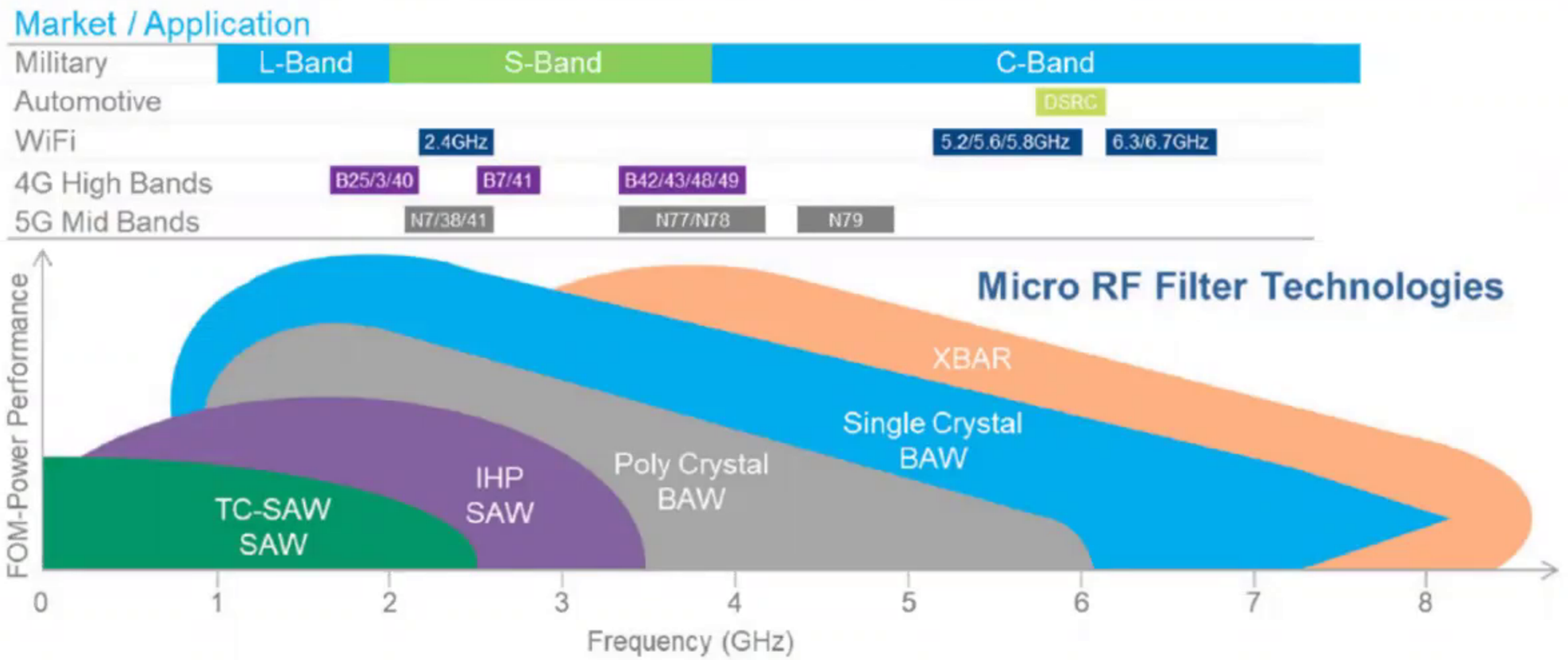


Figure 1. Market Application and Frequency Band Allocation of RF Filtering Technology [2].

Materials, Design, and Characteristics of Bulk Acoustic Wave Resonator: A Review, Liu et al, Micromachines (Basel). 2020 July 11(7): 630.

晶圓世界篇_POI _怕熱的SAW

2. FoM, K^2, Q, Temperature Compensation and Spurious Modes

王不老說半导