Microresonators in Titanium Nitride
New design and KID properties

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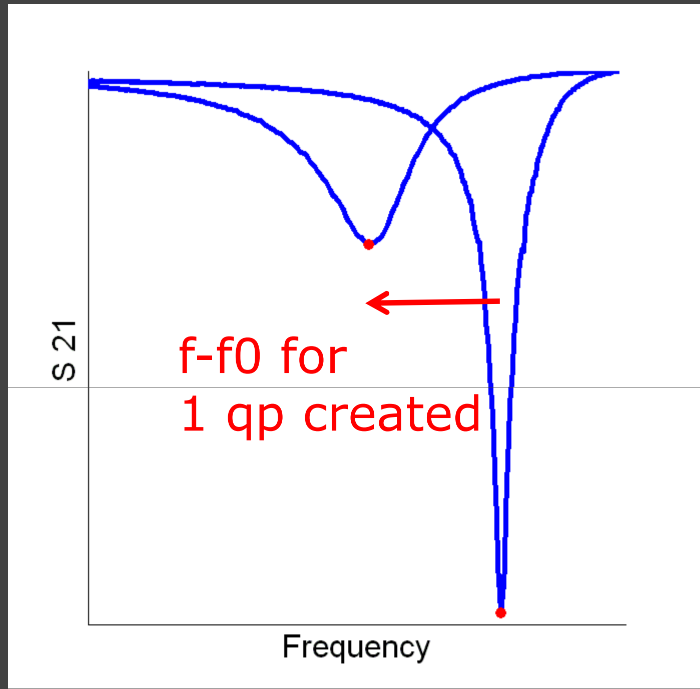
Why using high resistive material for KIDs ?

$$L_s \approx \hbar\rho/\pi\Delta t$$

δ (f-f0)/f0 / δ Nqp α Ls / (Lg+Ls)

Ex: Al KIDs 50nm: f-f0 ~ 0.1Hz / qp



The responsivity increases with ρ through Lk

Why Titanium Nitride ?

Leduc et al. APL 2010

$$L_s \approx \hbar\rho/\pi\Delta t$$

TiN – film used here:

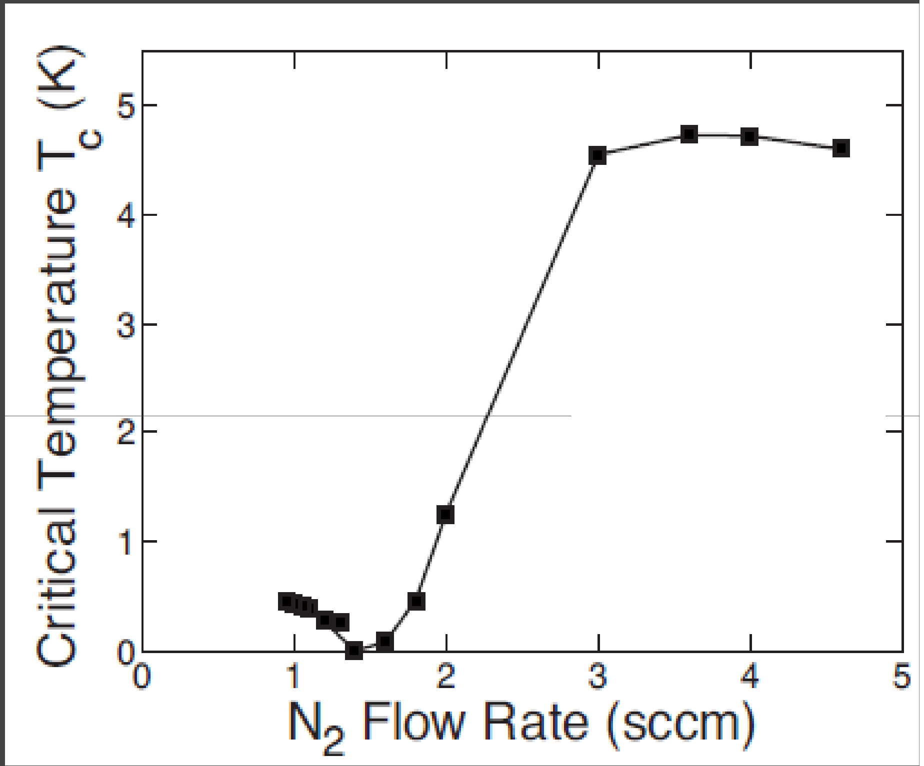
ρ≈130 μΩcm

Tc=0.8K → Δ= 125 μeV

→Ls ≈ 44 pH

(Aluminum : Ls<0.1pH)

Tc change with N_2 content



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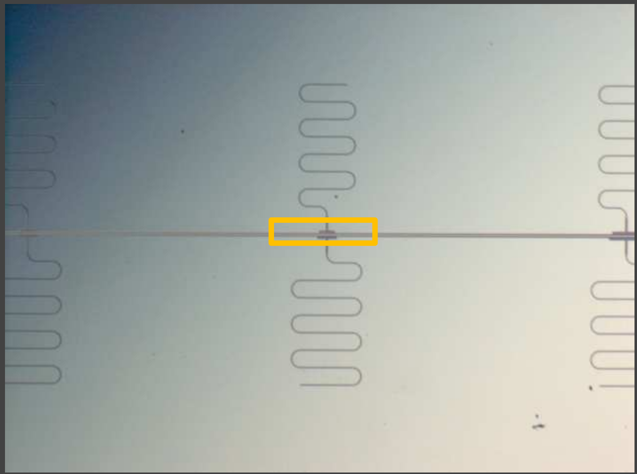
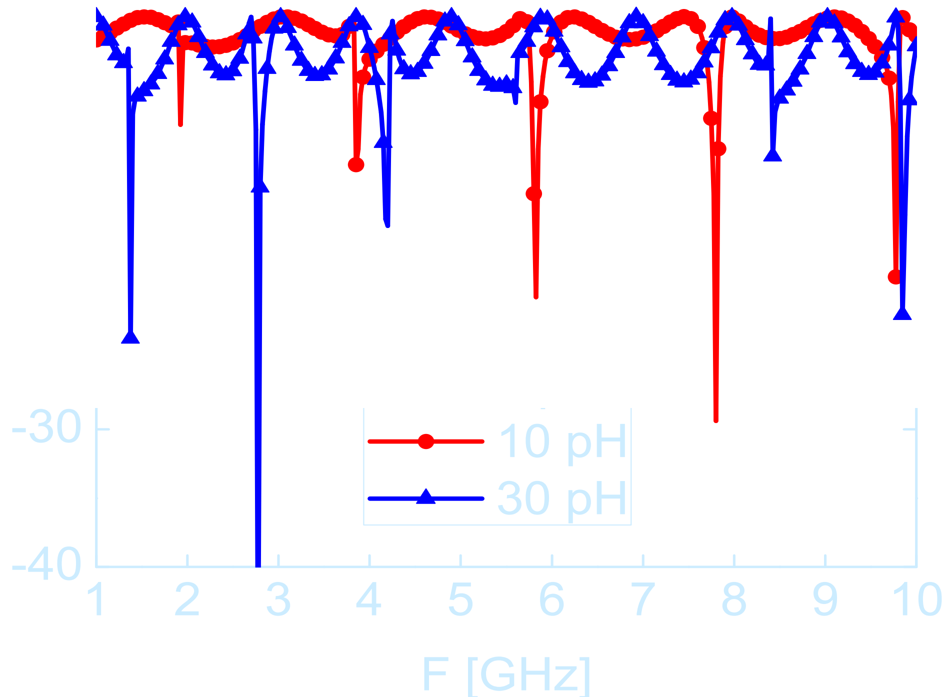
Microwave design need to be adapted

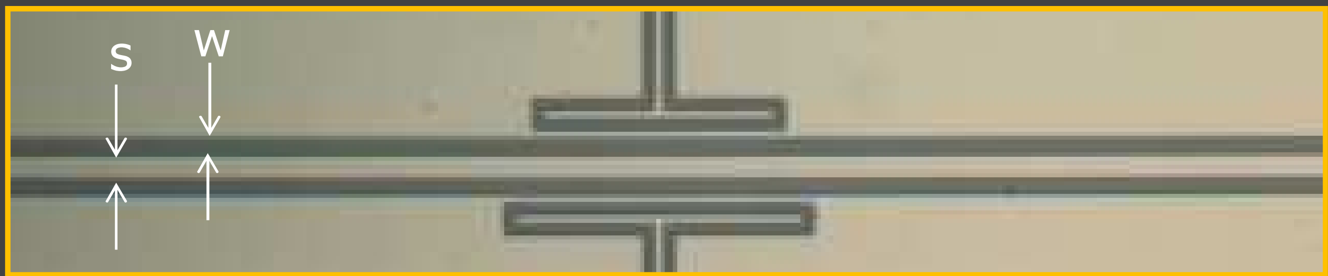
For a typical (Al) chip



PARASITIC DIP IN THE CHIP TRANSMISSION

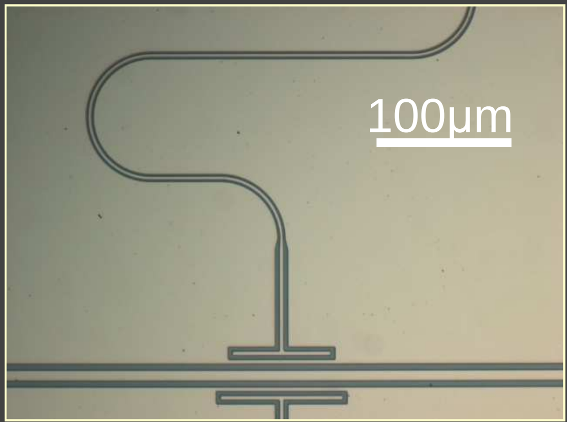


With
s=10μm
w=6 μm

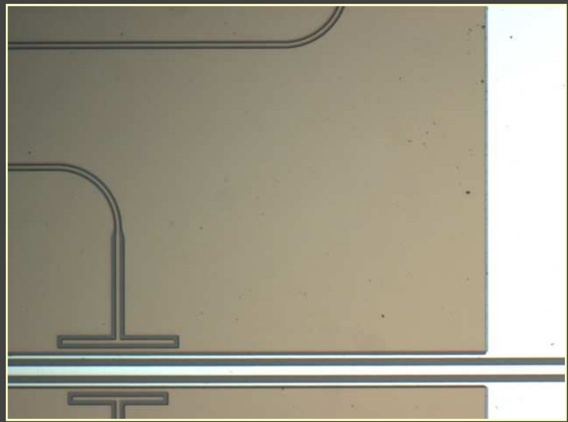


New hybrid design : KIDs TiN / Throughline Al

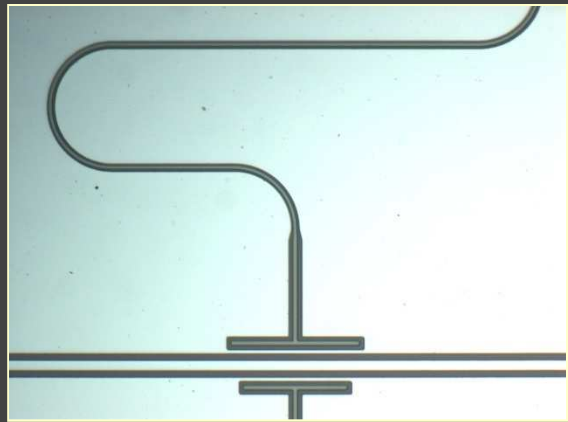
(to compare) Mono



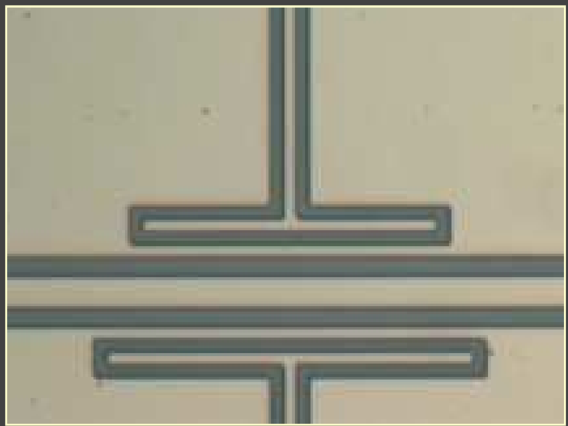
(hybrid) Duo

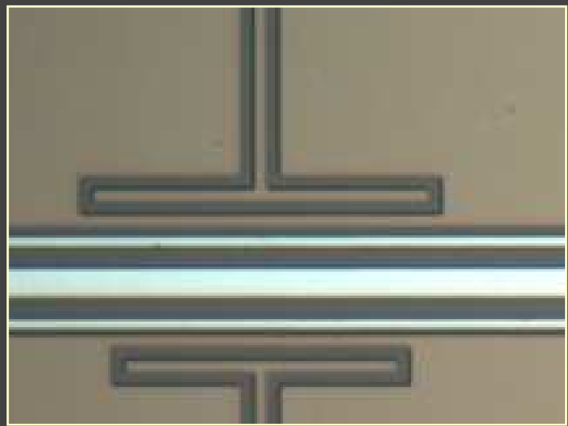


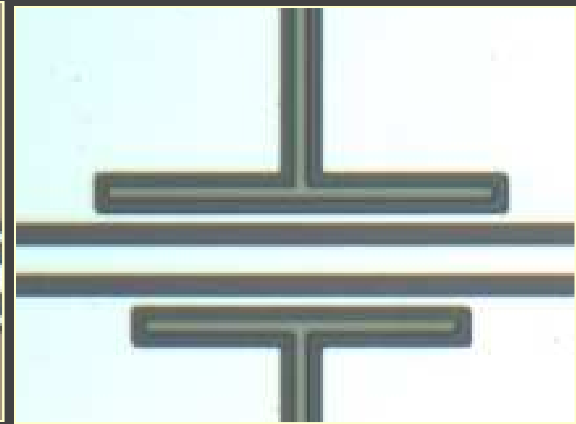
(Hybrid) KIDmix



Zoom x3:







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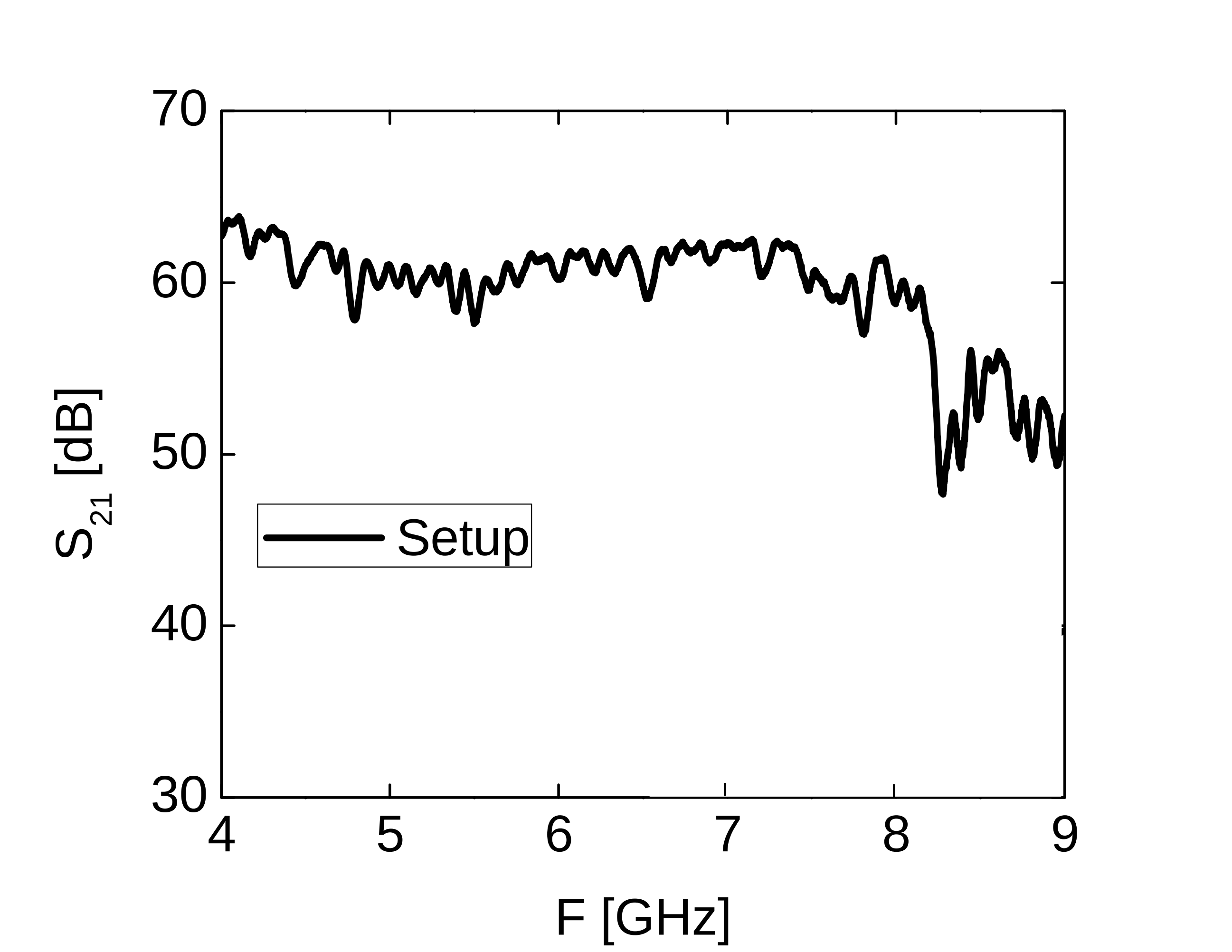
Lossless S21 transmission in the Hybrid designs



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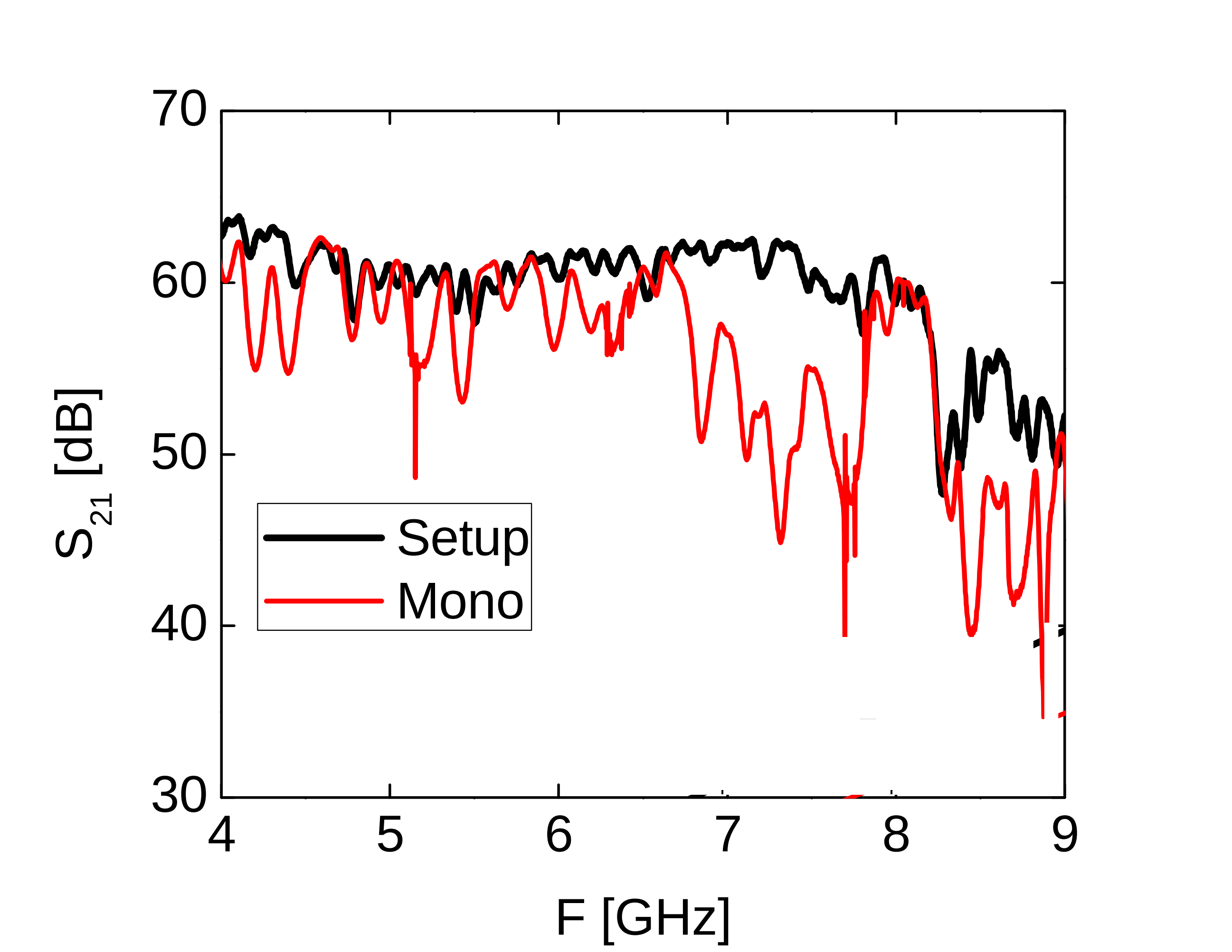
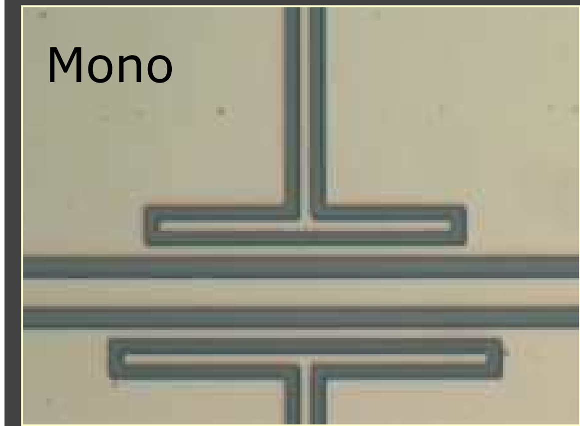
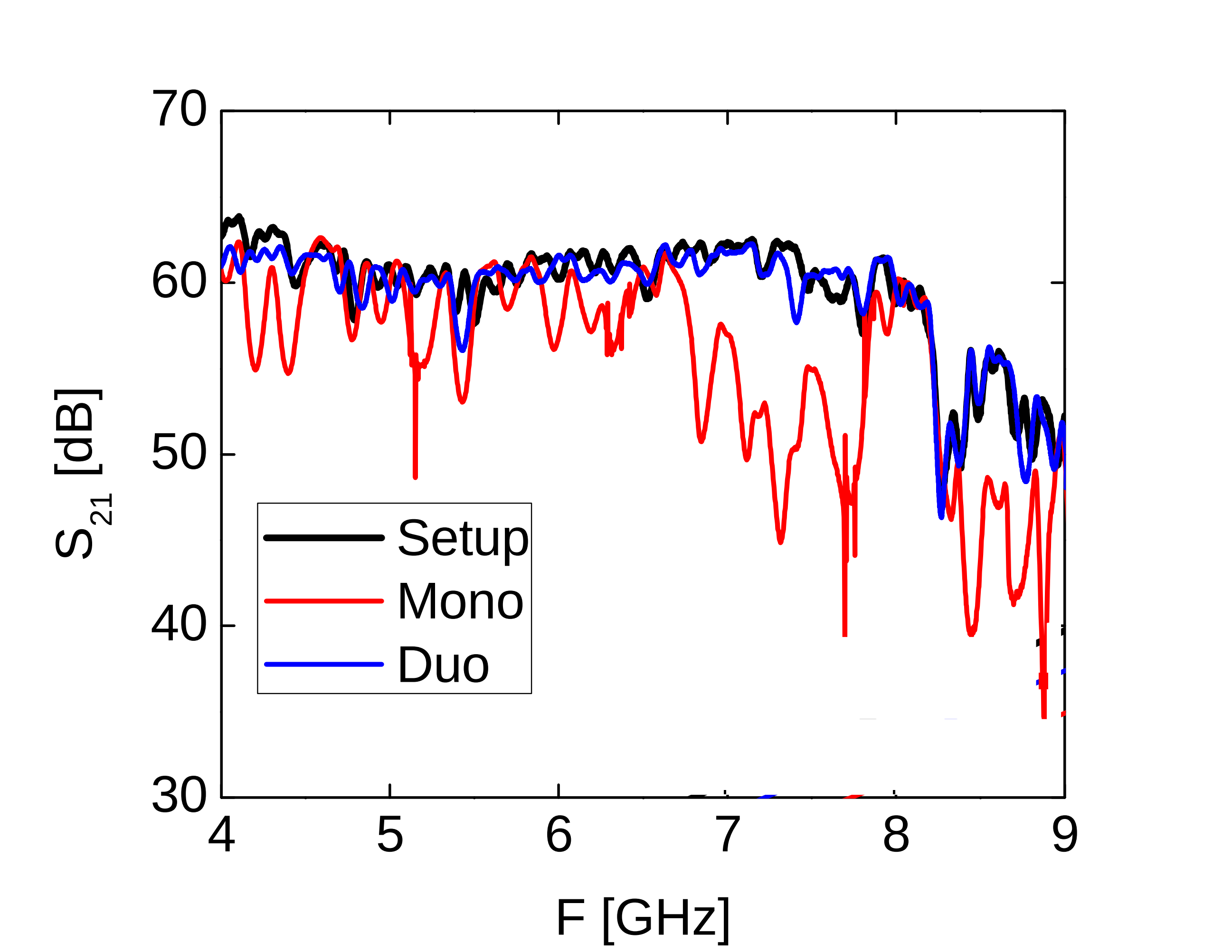
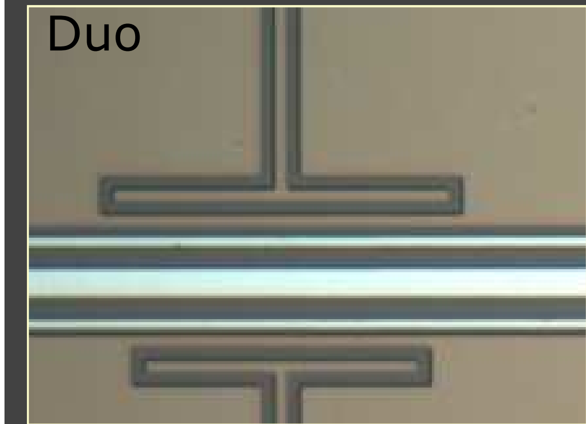
Lossless S21 transmission in the Hybrid designs



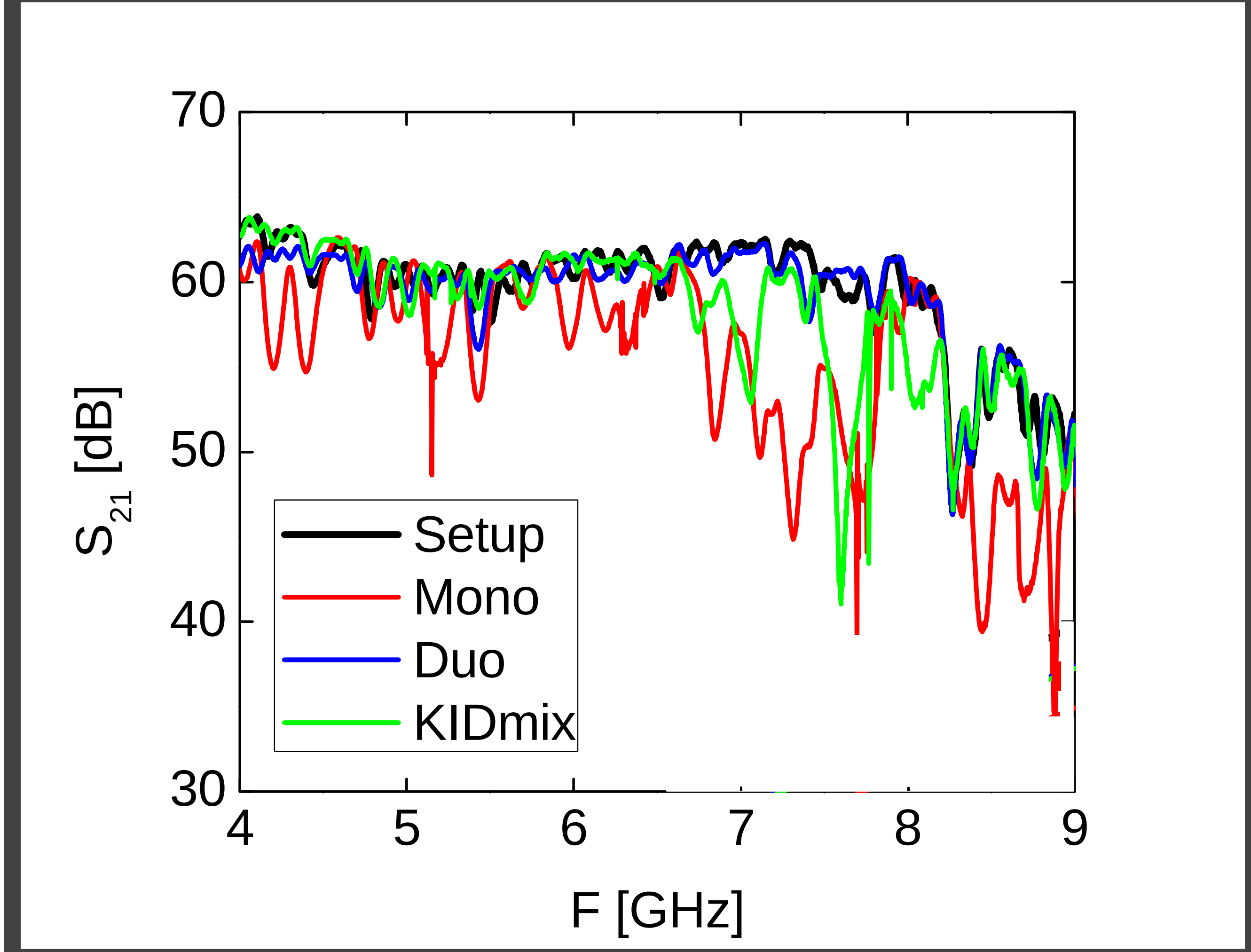


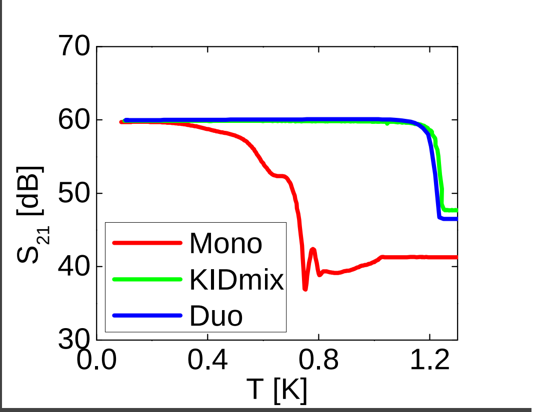
Lossless S21 transmission in the Hybrid designs

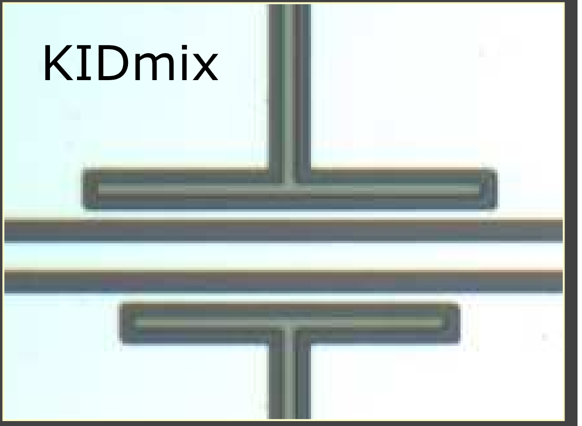




Lossless S21 transmission in the Hybrid designs

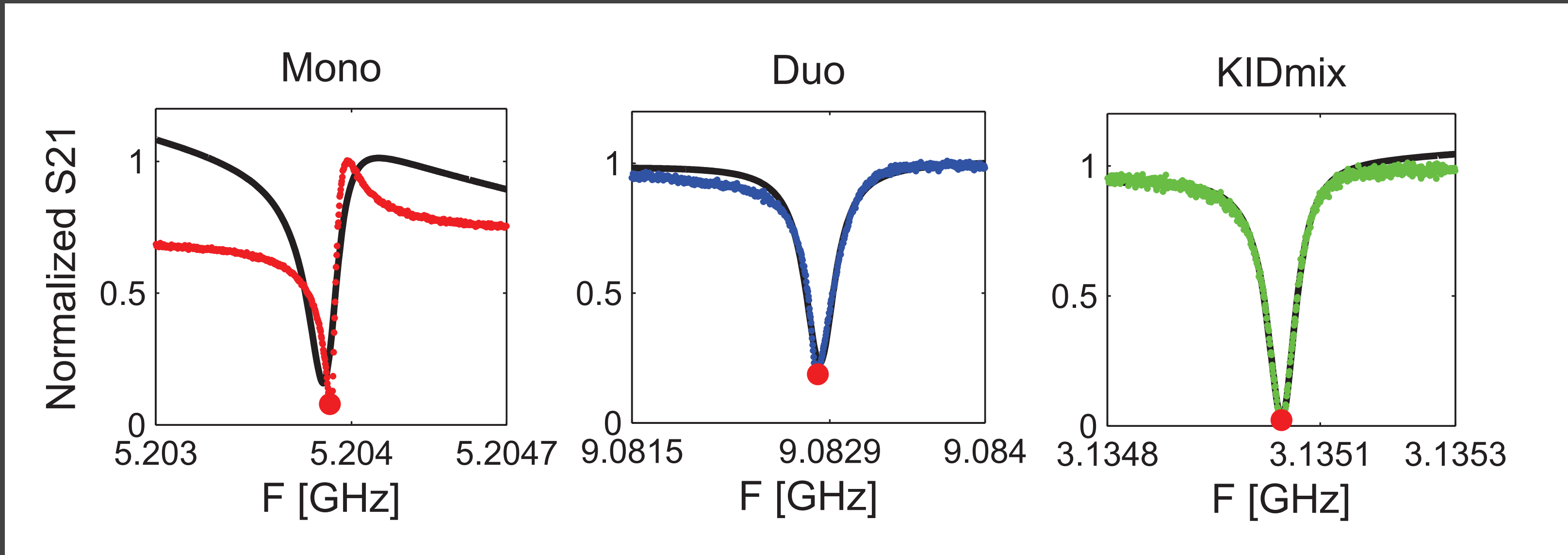






KID dips

fexp/fgeom= 0.2 → α = 96 %



$Q_i = 2\ 10^5$ $Q_i = 9\ 10^4$ $Q_i = 5\ 10^5$

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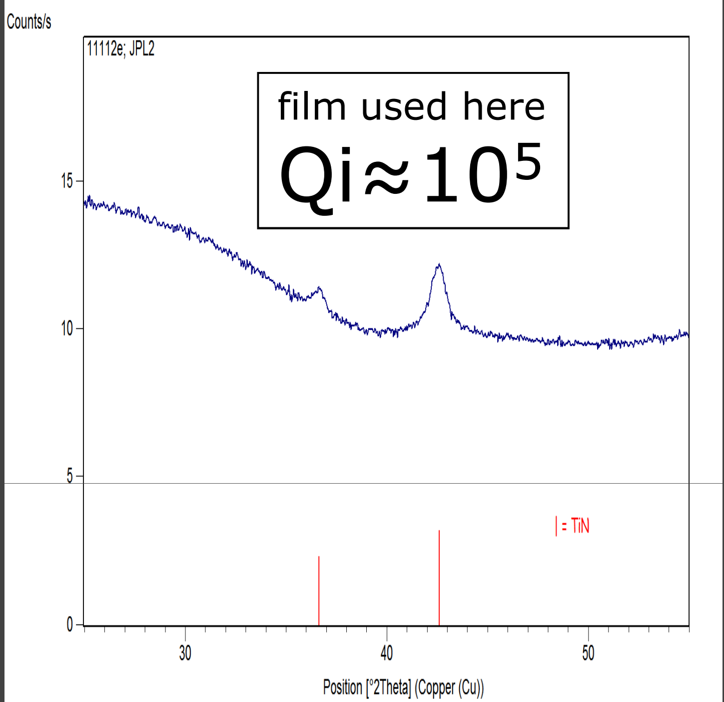
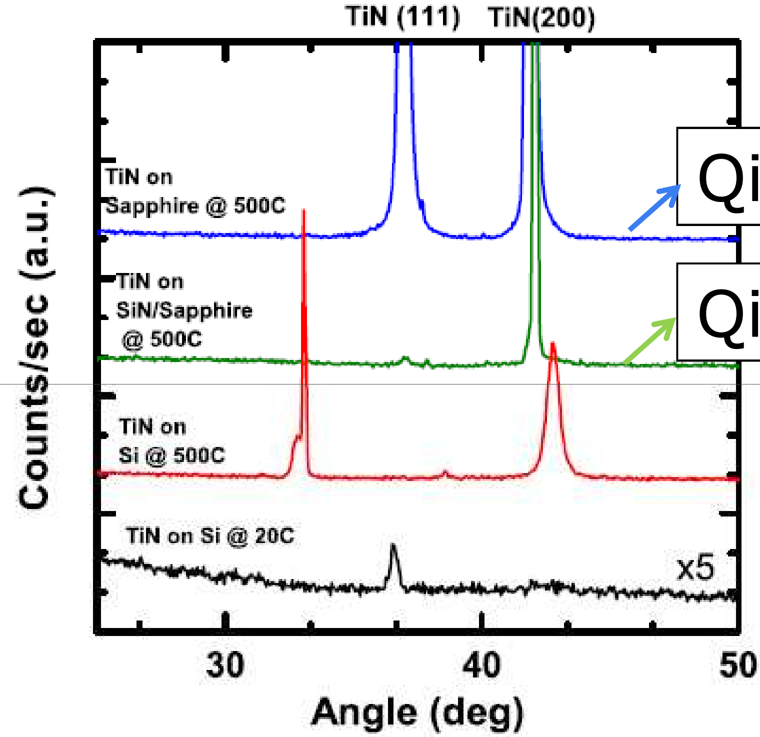
Note on Qi and crystalline orientation - by XRD



film used here
$Qi \approx 10^5$

Vissers et al.

Appl. Phys. Lett. **97**, 232509 (2010)

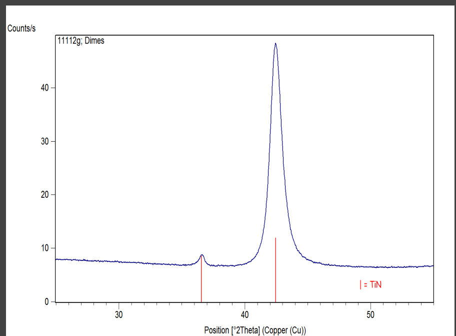


$Qi \approx 10^5$

$Qi \approx 10^7$

FIG. 2. (Color online) $\theta - 2\theta$ XRD scans of TiN films on sapphire, Si and SiN/Si at 500 °C, and Si at 20 °C. The (111)-TiN peak at $2\theta=36$ ° is present on the sapphire substrate as well as for Si room temperature. The TiN grown at high temperature on Si and SiN both exhibit primarily (200)-TiN peak at 2θ around 42 °. The sharp peak at 33 ° on high temperature TiN on Si is due to the XRD being performed on a patterned sample with exposed Si regions.

film from DIMES/Delft
$Qi \approx 10^7$



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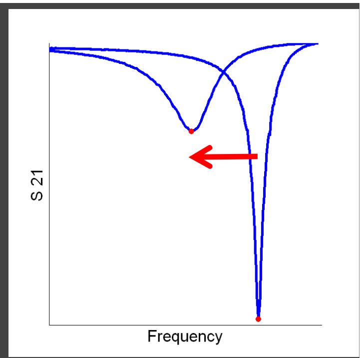
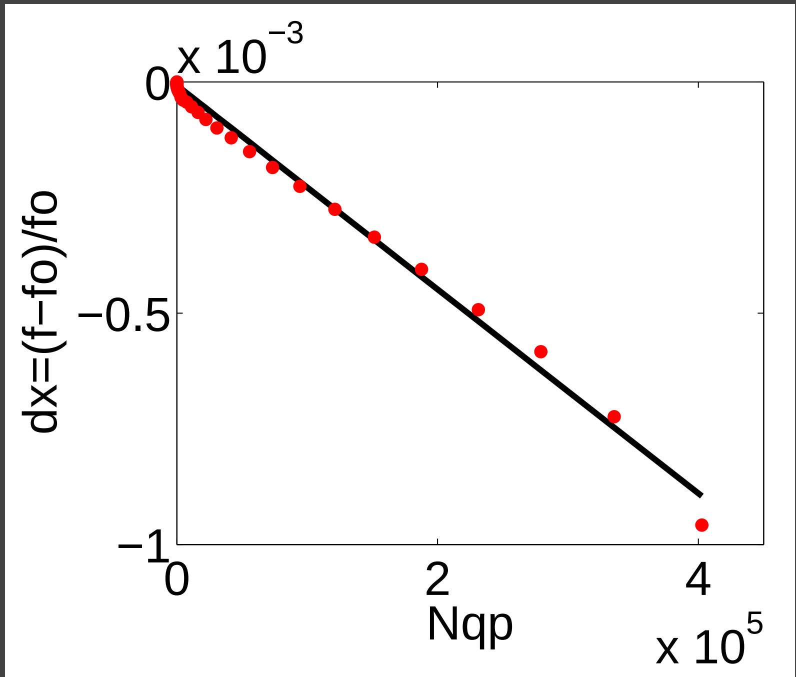
Large responsivity

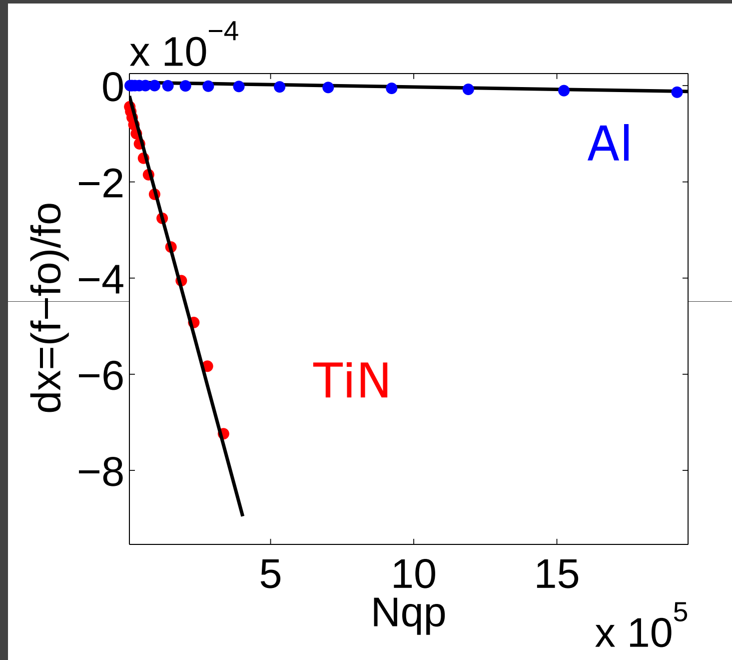
$$N_{qp}(T) = 2VN_0\sqrt{2\pi k_B T \Delta} exp\left(-\frac{\Delta}{k_B T}\right)$$



TiN Tc=1K



Comparison with Al



$f-f_0$ ~ 10 Hz / qp

$f-f_0$ ~ 0.1 Hz / qp

($dx / dNqp = 2.2 \times 10^9$)

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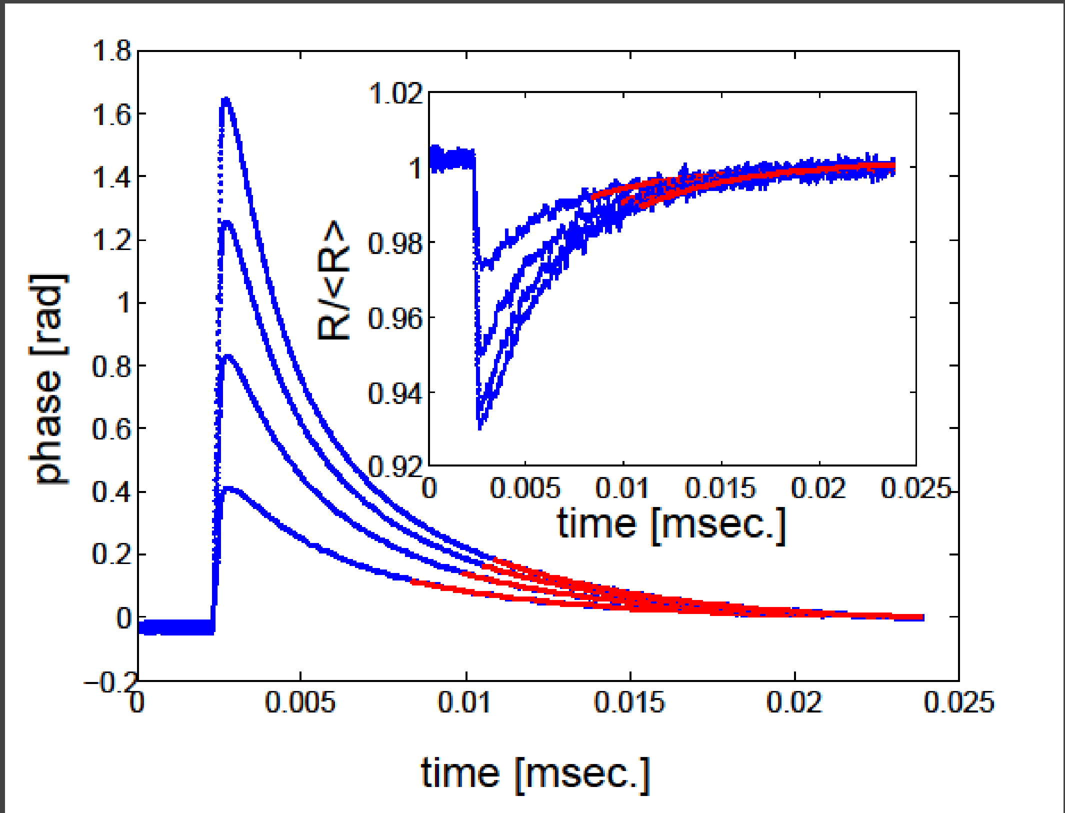
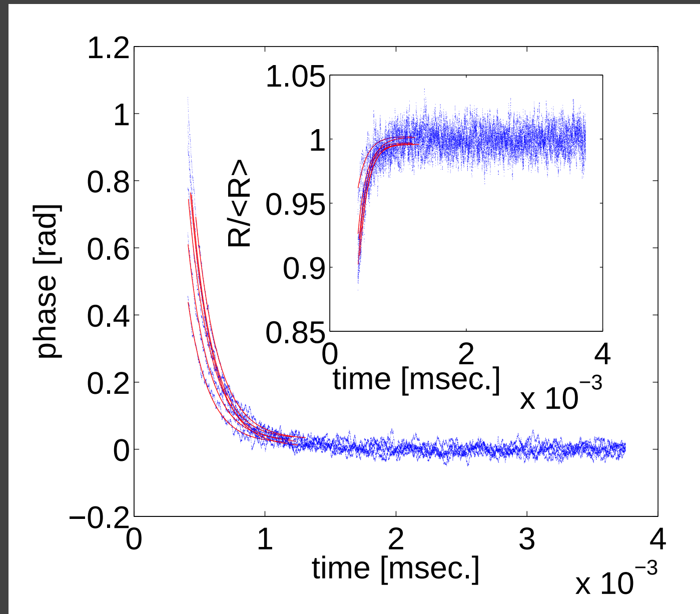
Lifetime





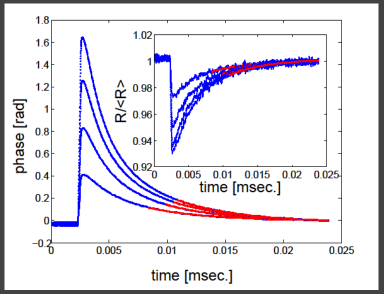
$\tau = 0.17$ ms

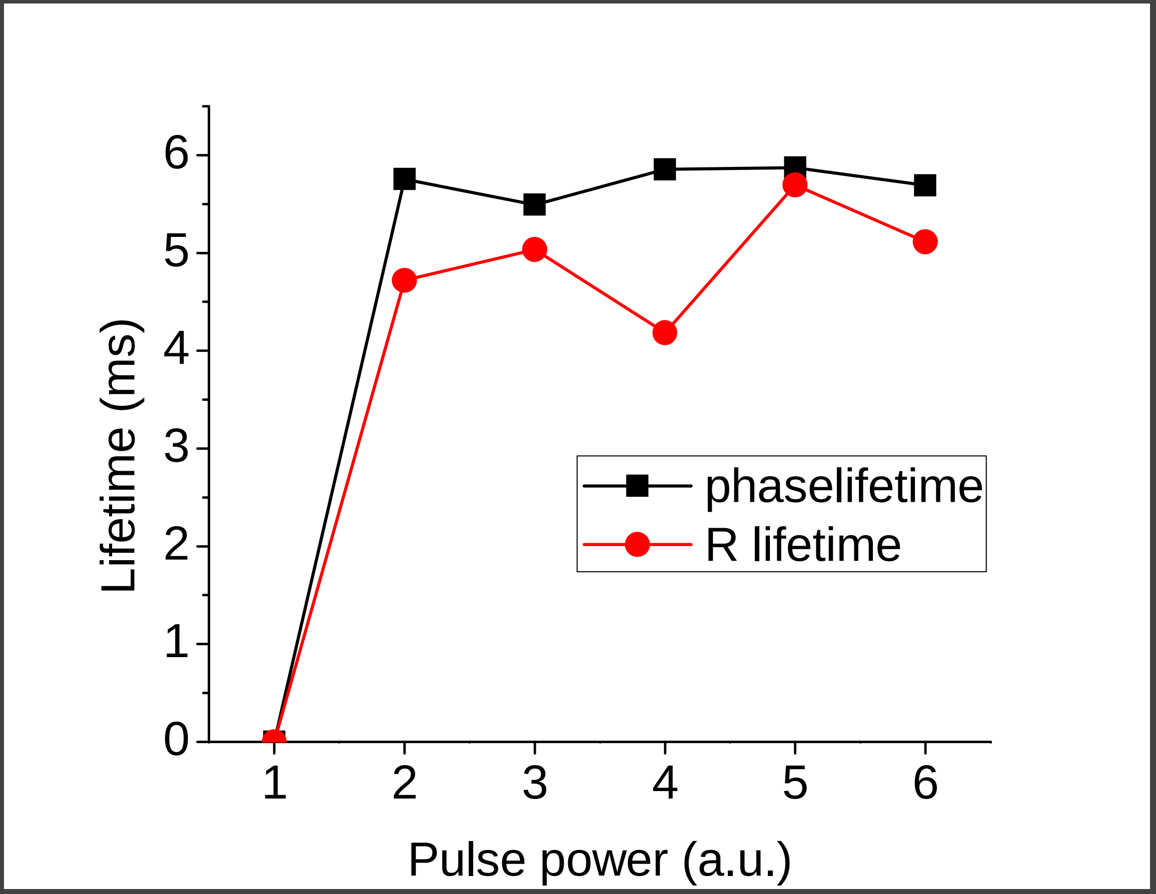
As high as 5.6 ms

But large variations between KIDs

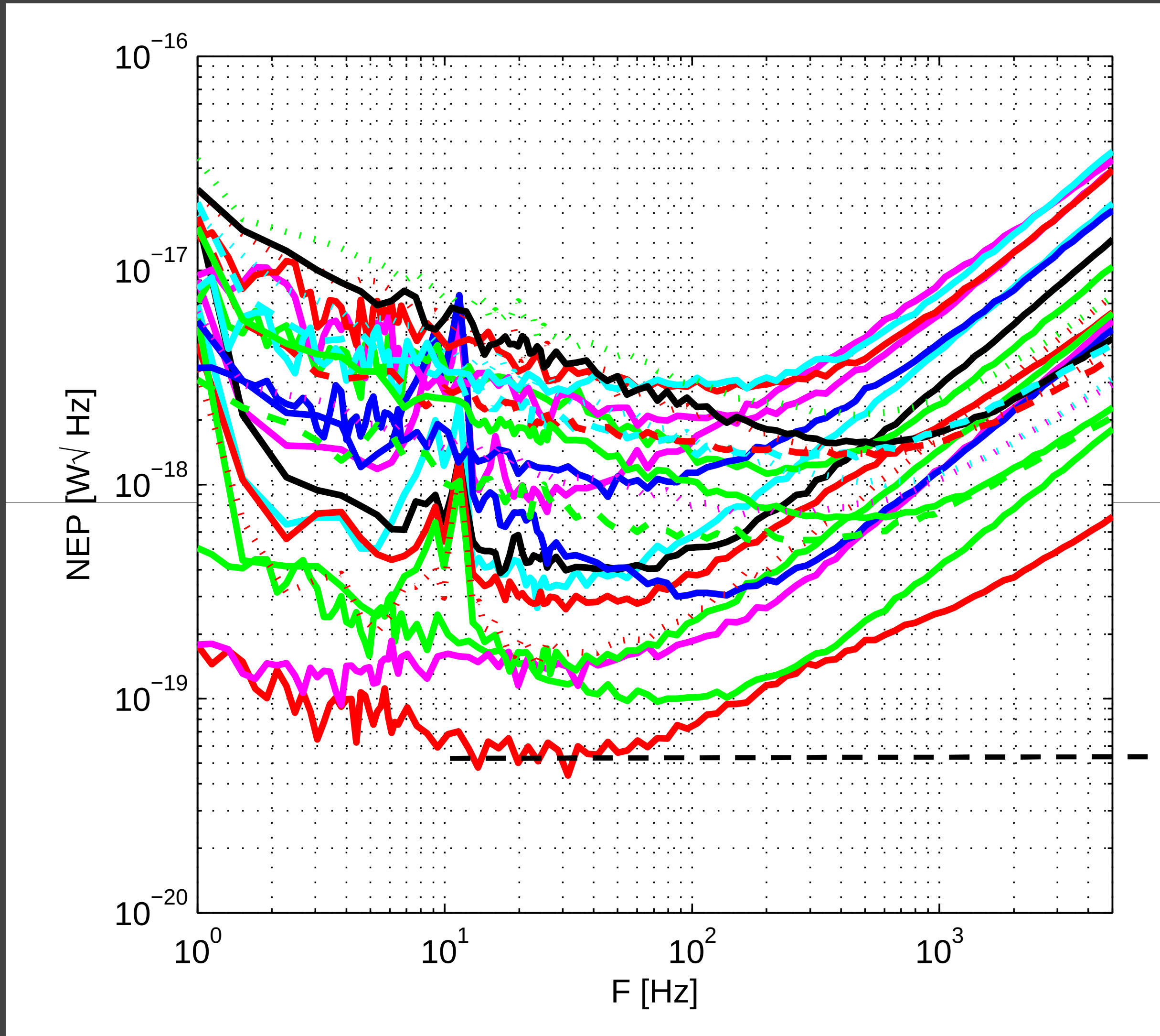
Lifetime

Check of the data giving $\tau = 5.6$ ms





Electrical NEP (in phase)



Best NEP :
4 x 10^{-20} W√Hz

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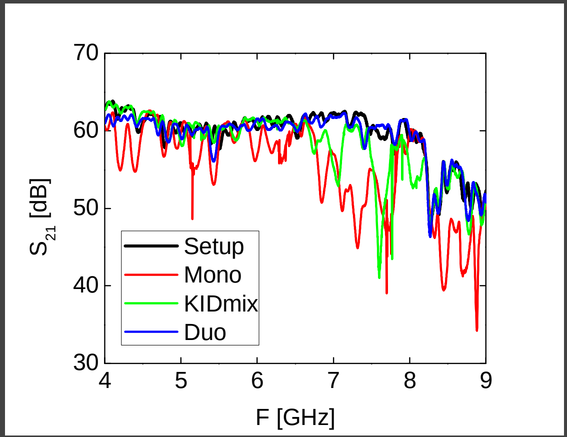
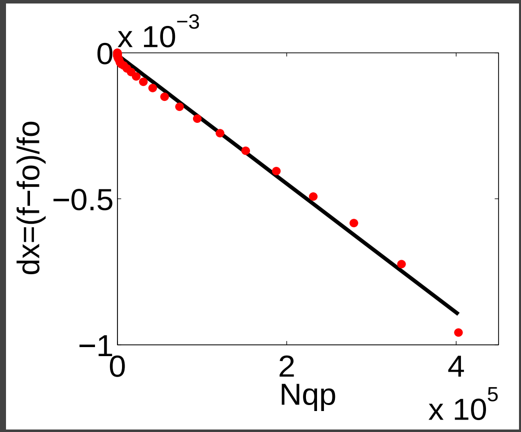
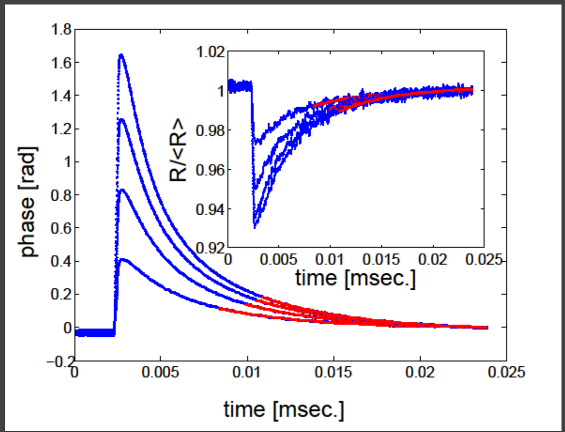
Conclusions



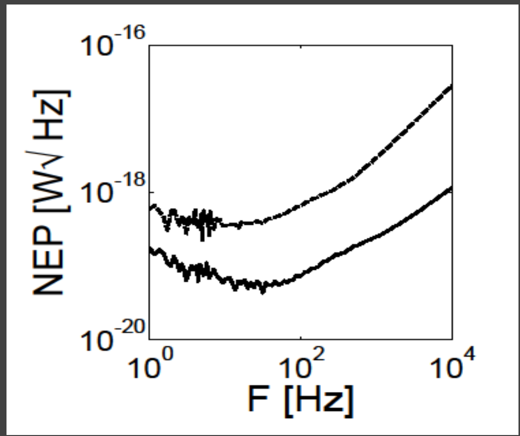
New design



Large responsivity



Lifetime up To 5.6 ms



Best NEP : 4×10^{-20} W√Hz

The reproducibility between KIDs is now the big issue

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Collaboration

SRON	Jochem Baselmans Steve Yates Jan-Joost Lankwarden
JPL	Rick Leduc Loren Swenson for the KISS group
TU Delft	Pieter-Jan Coumou Hugo Schellevis Akira Endo Teun Klapwijk
Cardiff U.	Simon Doyle Julie Gould

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Example of NEP calculation for the best KID

following the classical analysis described in [Baselmans&al J Low Temp Phys (2008) 151: 524–529]

$$NEP_\theta = \frac{\sqrt{S_\theta}}{\left(\frac{\eta\tau}{\Delta}\frac{\delta\theta}{\delta x}\frac{\delta x}{\delta N_{qp}}\right)}(1+\omega^2\tau^2)(1+\omega^2\tau_{res}^2)$$

$S_\theta = -63dBc/Hz = 10^{-63/10}rad^2/Hz$ noise, measured at 100Hz, 100mK, with optimal power -102dBm (purple curve)

$\eta = 0.57$ efficiency of quasiparticle creation

$\tau = 3.68ms$ quasiparticle lifetime, measured at 100mK

$\Delta = 125\mu eV = 2.00\,10^{-23}J$ superconducting gap, from $\Delta = 1.81k_BTc$ [Escoffier&al PRL 2004] and $Tc = 0.8K$ measured in this chip with S21(T)

$\frac{\delta\theta}{\delta x} = \frac{4Q}{f_0}$ with $Q = 2.91\,10^{-4}$ the measured (loaded) quality factor and $f_0 = 5.20GHz$ the KID frequency at 100mK

$x(T) = \frac{f(T)-f_0}{f_0}$

$\frac{\delta x}{\delta N_{qp}} = -2.21\,10^{-9}$ linear fit between 100 and 200mK of the measured frequency response.T is translated to Nqp via the relation:

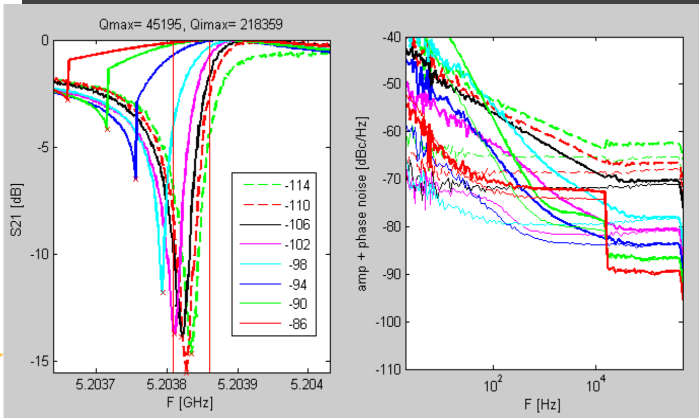
$N_{qp}(T) = 2VN_0\sqrt{2\pi k_BT\Delta}exp\left(-\frac{\Delta}{k_BT}\right)$ with $V = 4056\mu m^2\times 50nm$ the volume of the resonator and $N_0 = 8.7\,10^9eV^{-1}\mu m^{-3}$ from [Leduc&al APL 2010]

$(1+\omega^2\tau^2)(1+\omega^2\tau_{res}^2)$ frequency cut off due to the qp and resonator ring time - can be neglected here

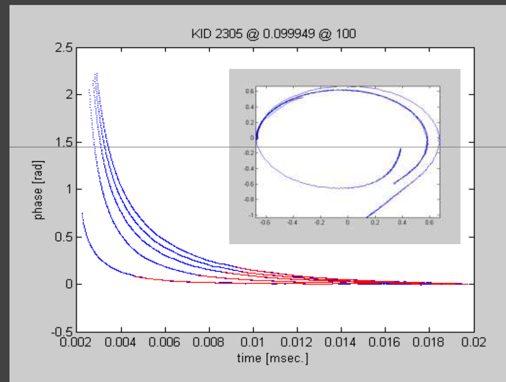
Putting all together:

$NEP_\theta = 5\,10^{-20}W\sqrt{Hz}$

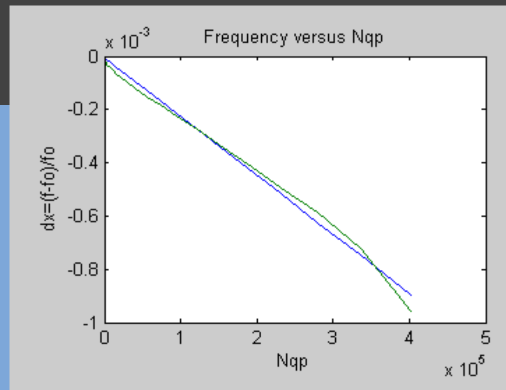
S_θ measurement



Lifetime

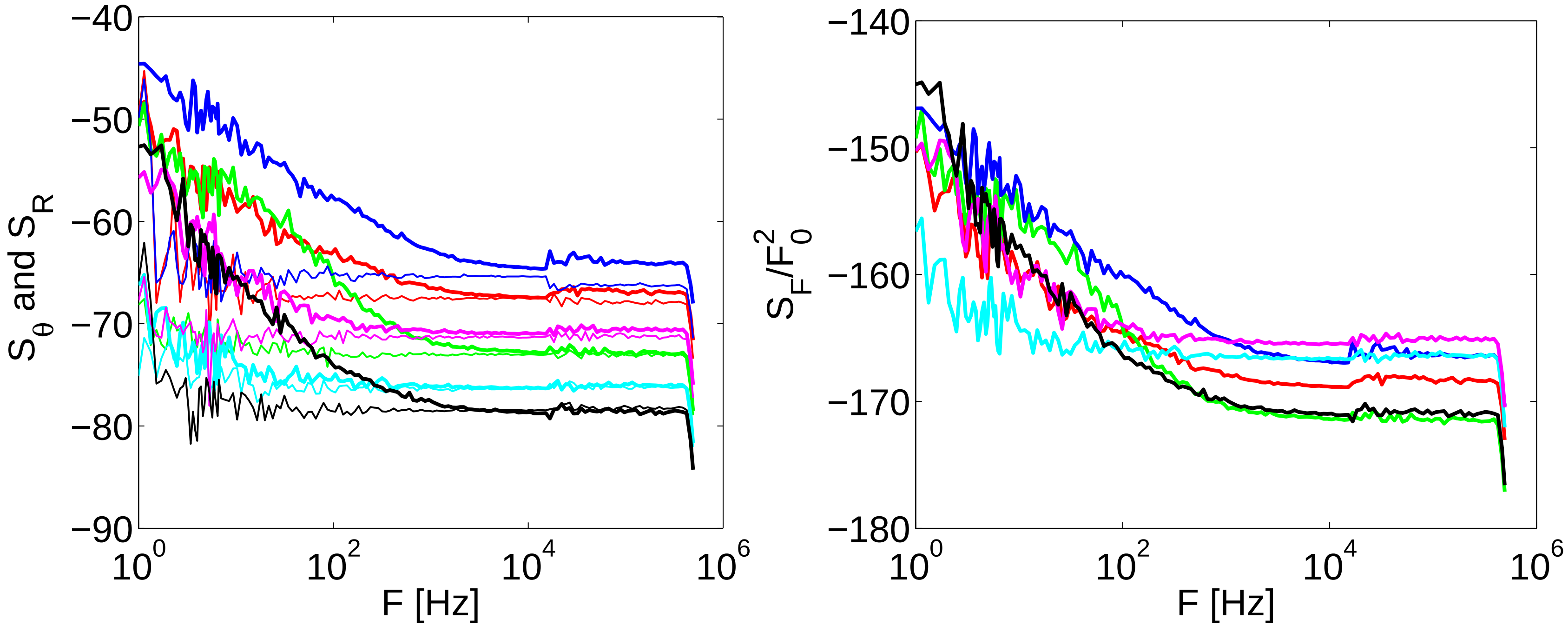


Frequency response



Noise

(in Duo)



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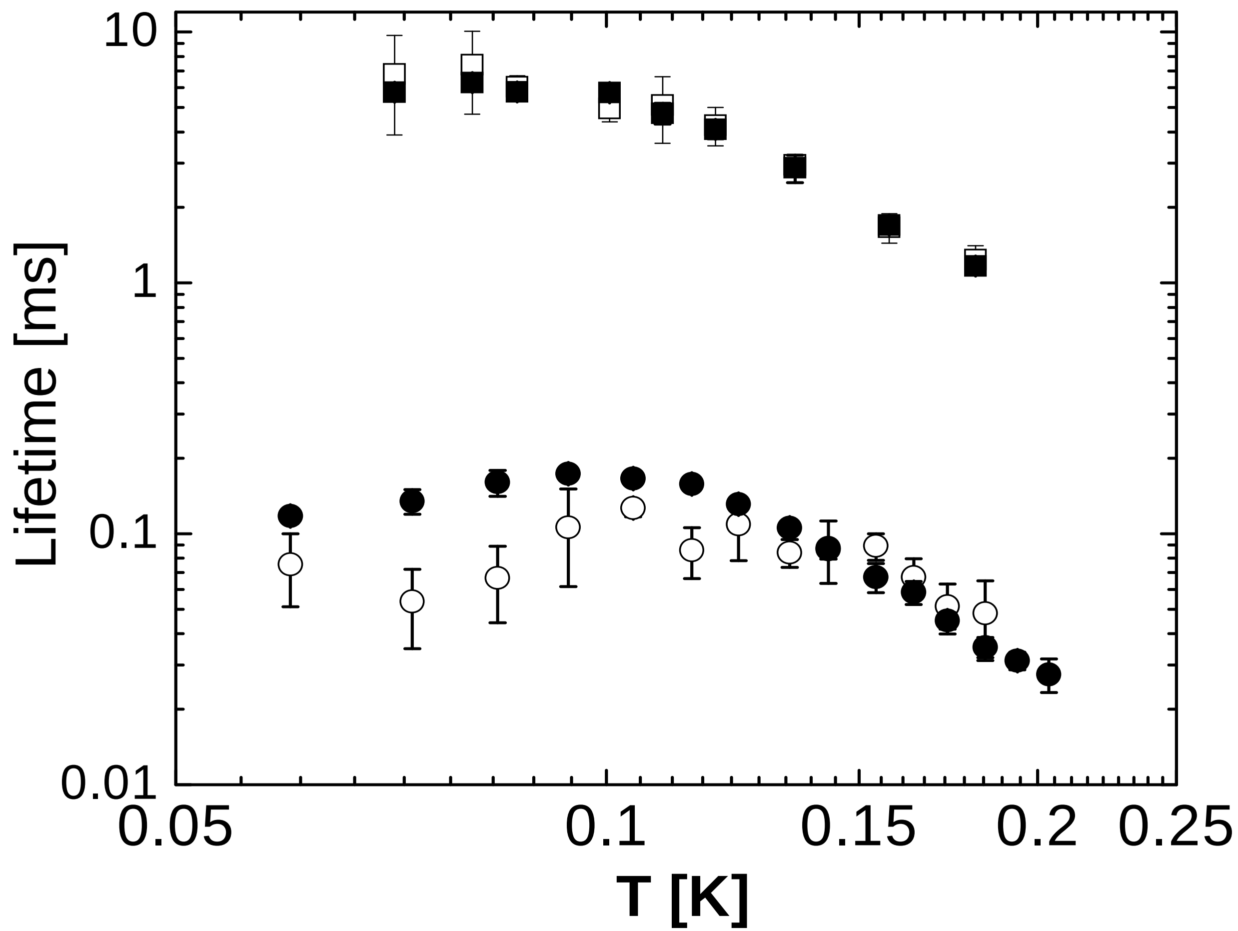
Lifetime 3



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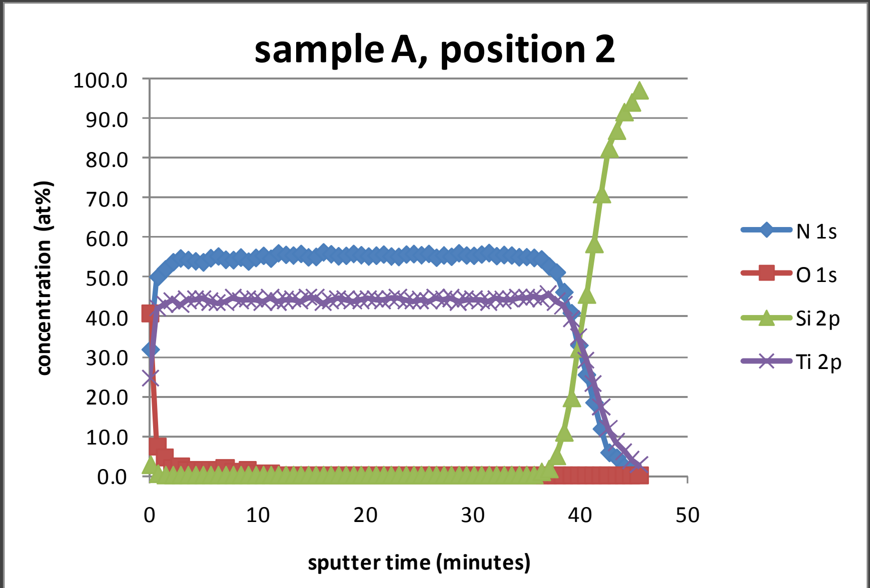
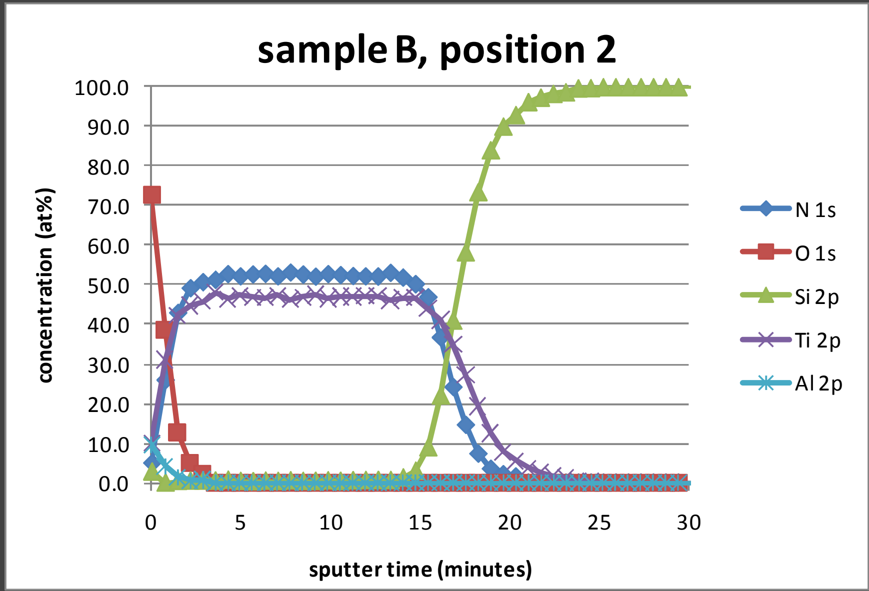
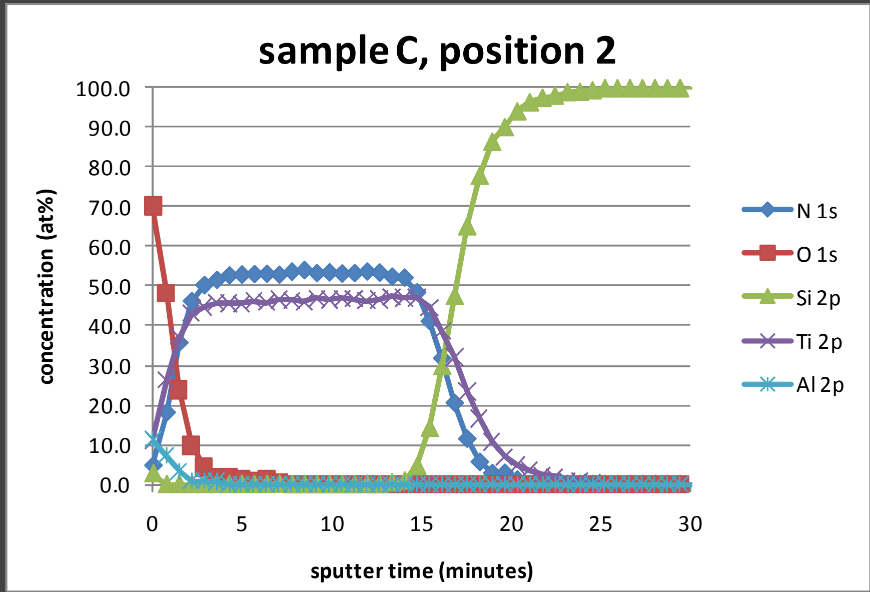
Internal Q factor 2







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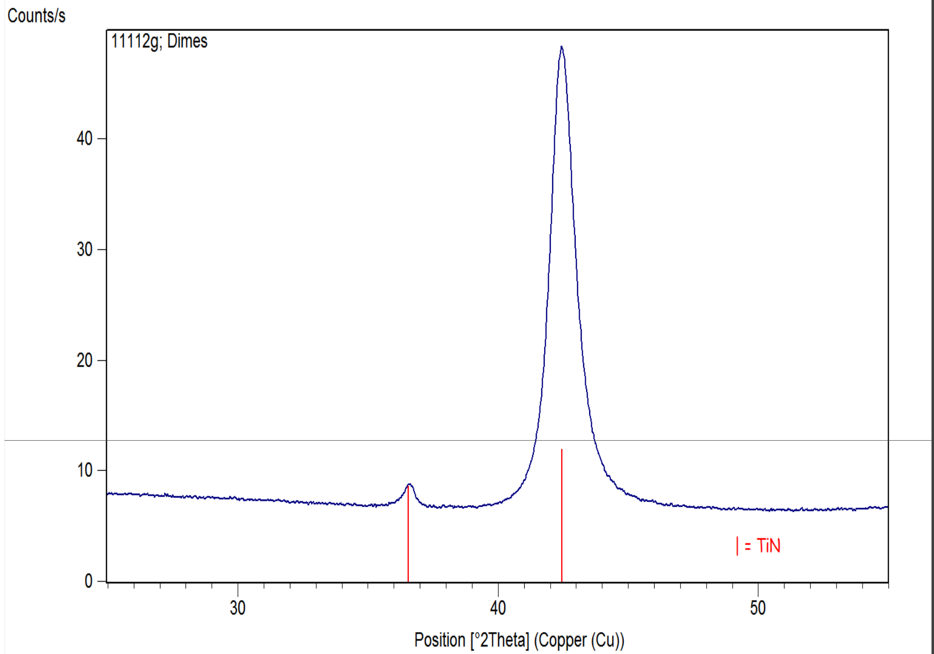
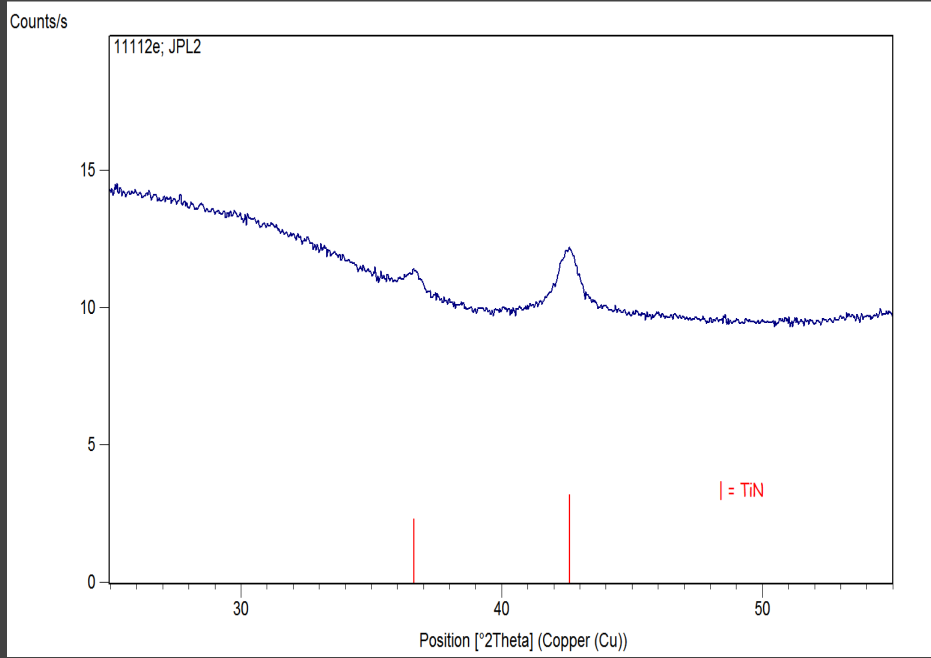
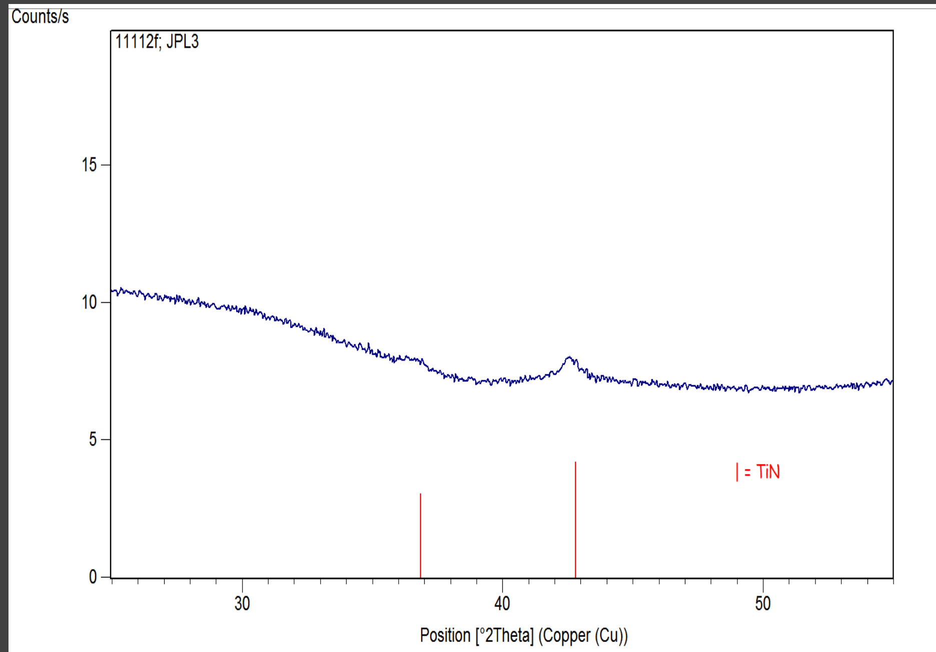
Internal Q factor 4







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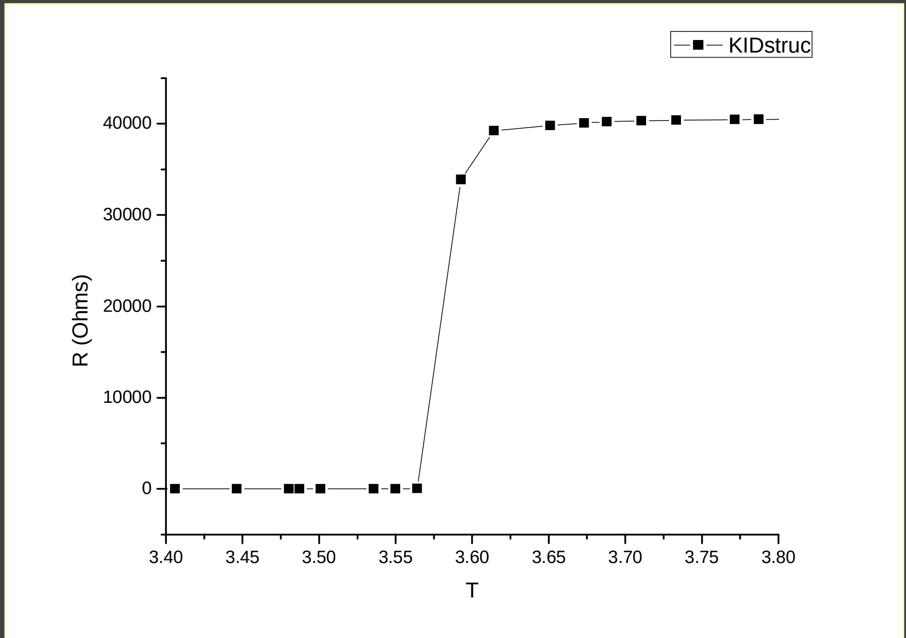
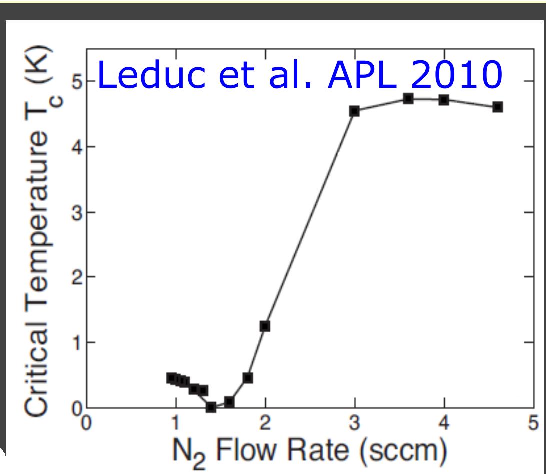
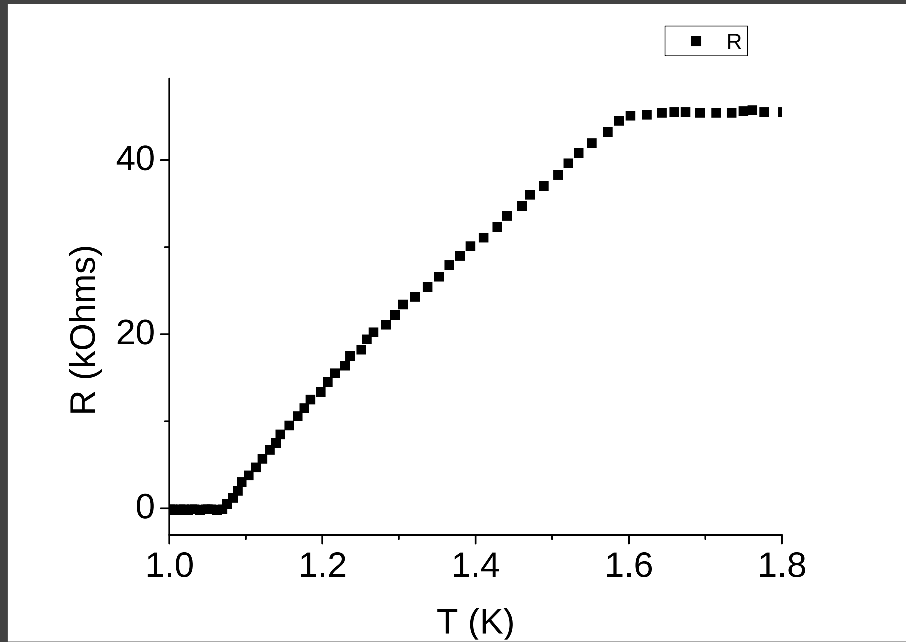
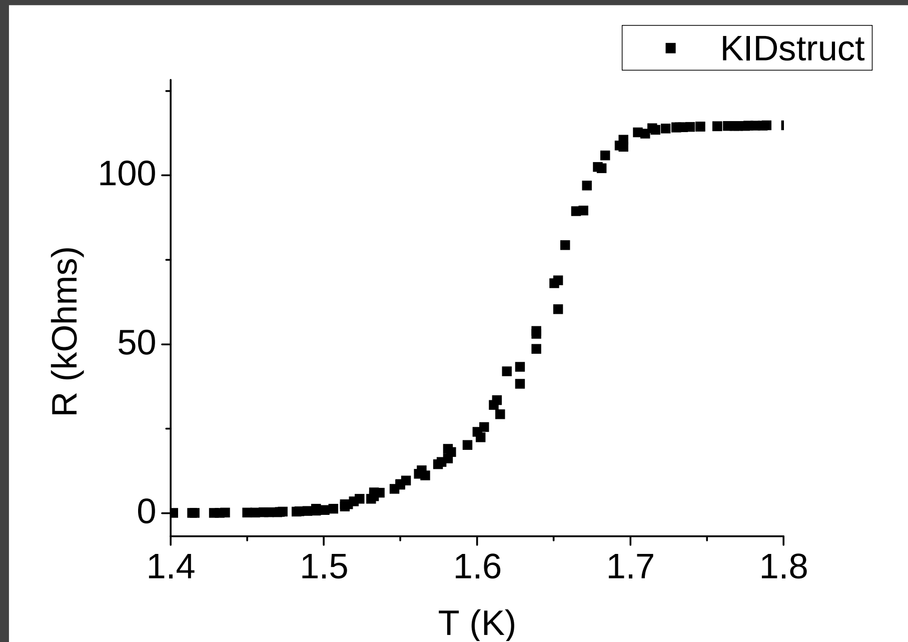
Internal Q factor 1

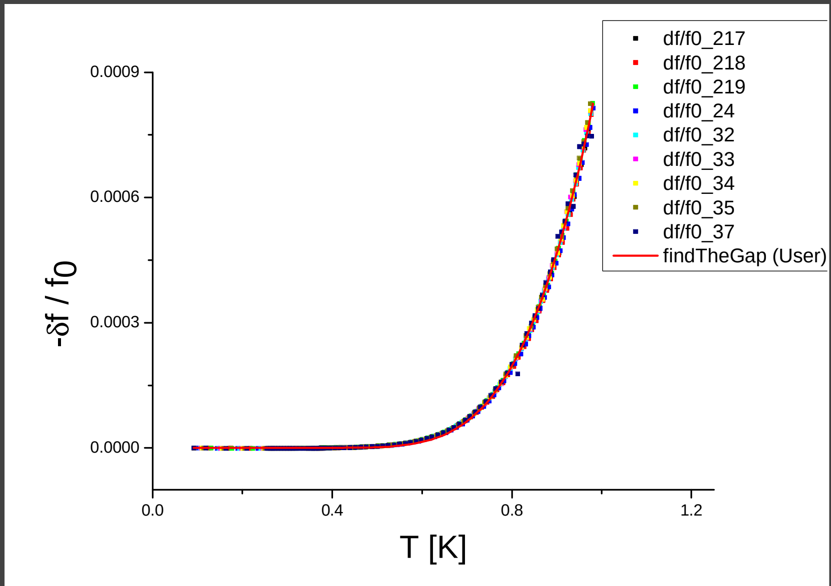


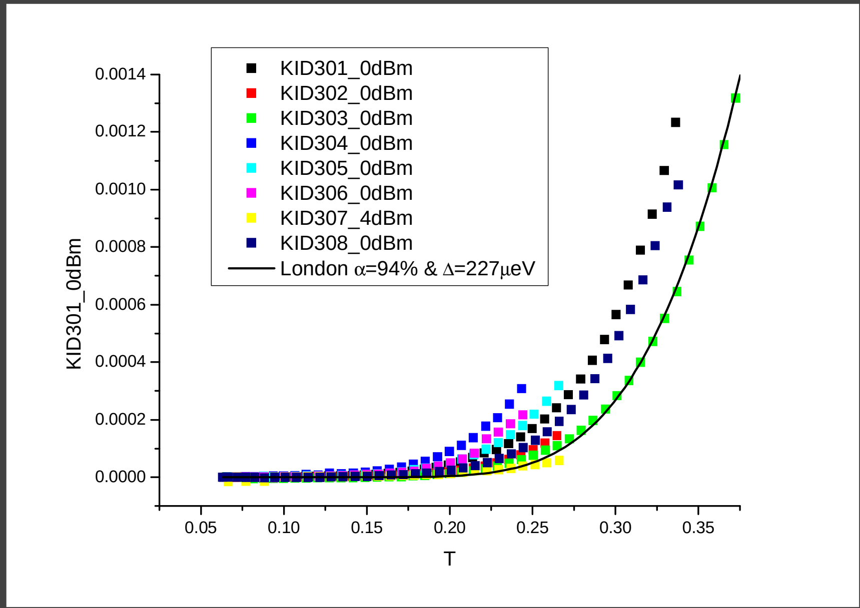






Responsivity 1





Gap=0.57meV (6.67K)

Tc=3.6 K

→ gap/kTc=1.85

Escoffier&al PRL04: gap/Tc=1.81 (STM/S meas.)

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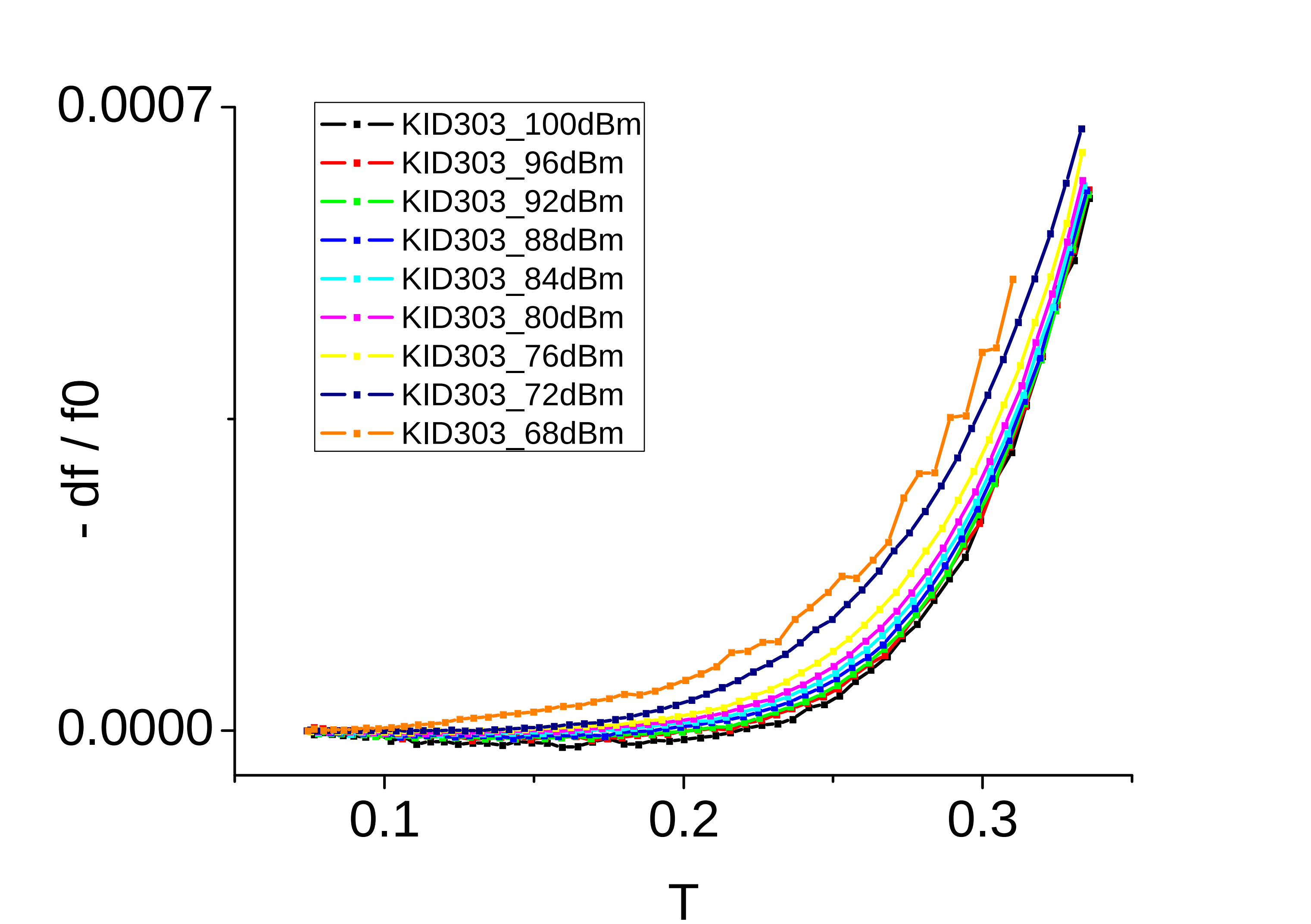
Responsivity 2



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LeKIDs designs for optical chips – Simon Doyle