Development of diamond based KIDs

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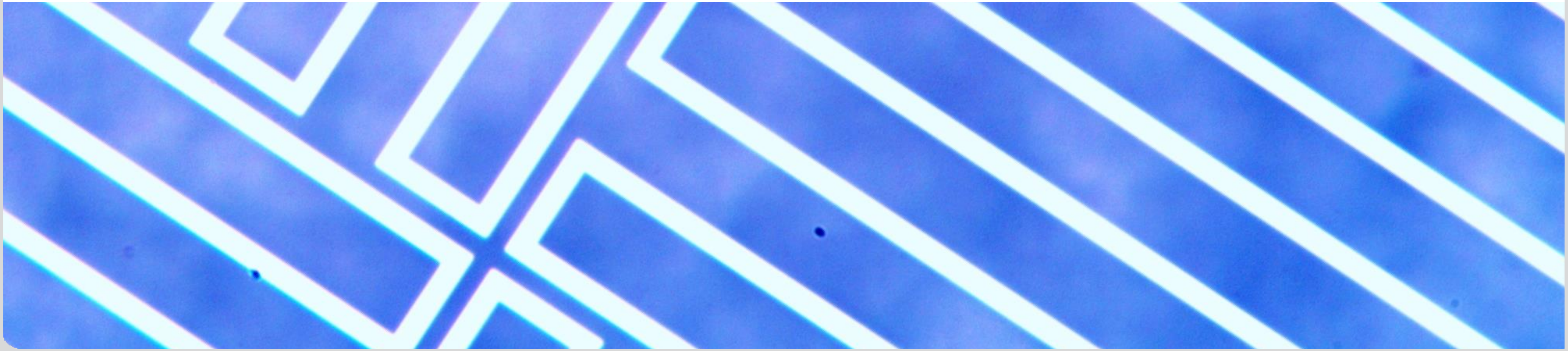


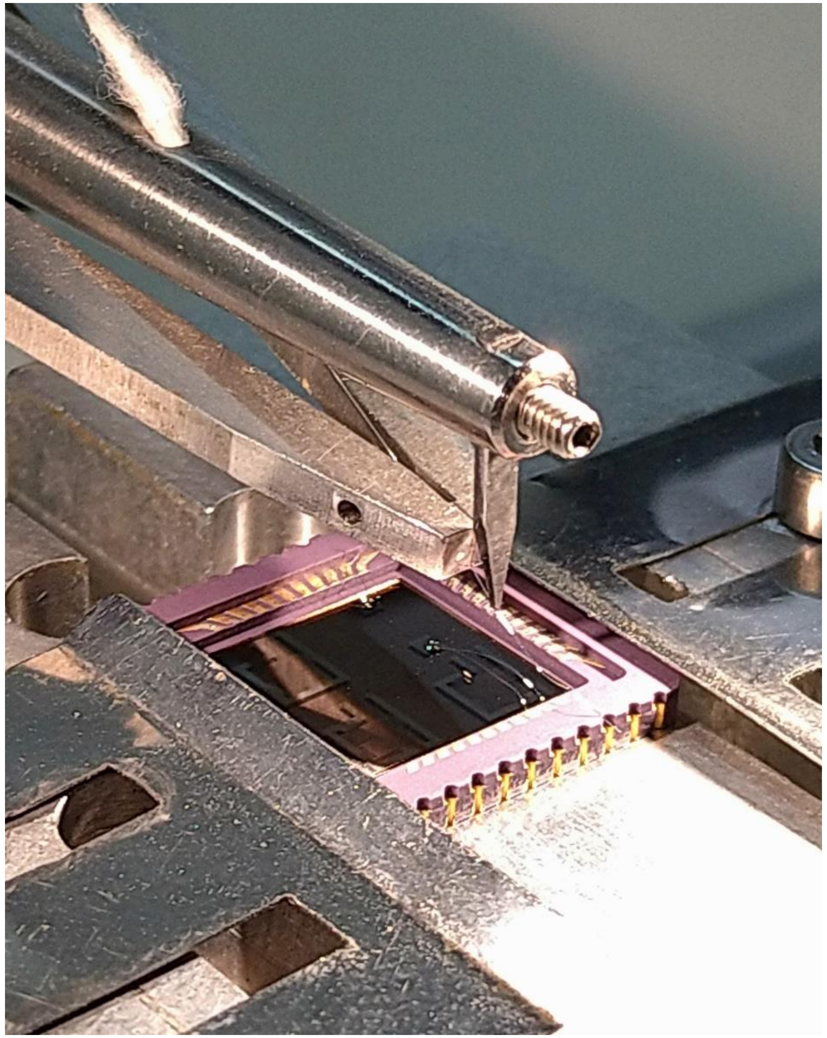
Contents

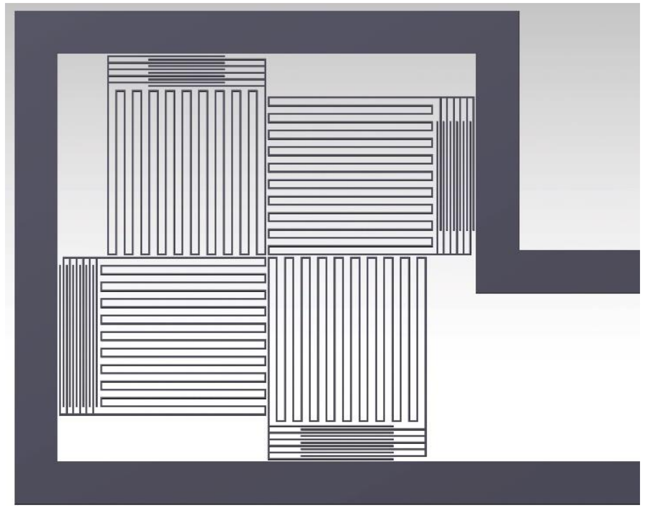
1. Introduction
   - Application
   - Kinetic Inductance Detectors
   - Why diamond?

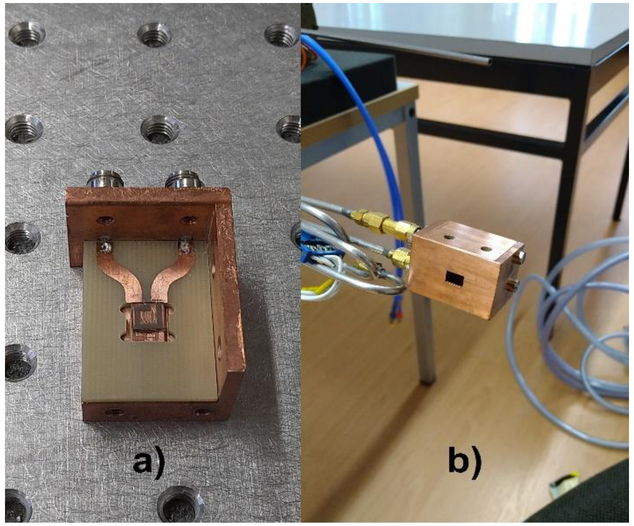
2. Simulations
   - Frequency tuning
   - Cross-Talk analysis
   - Quality factors tuning
   - Complete detector simulations

3. Experiments
   - SC thin film characterization
   - Microwave characterization
   - THz characterization

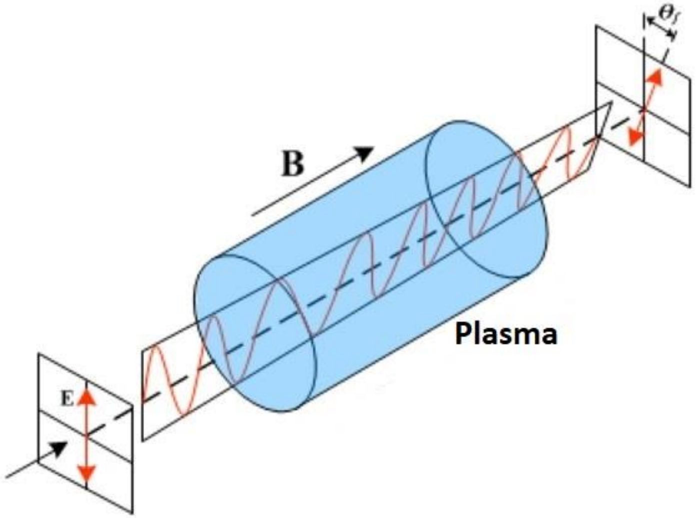
4. Conclusions







Introduction – Application



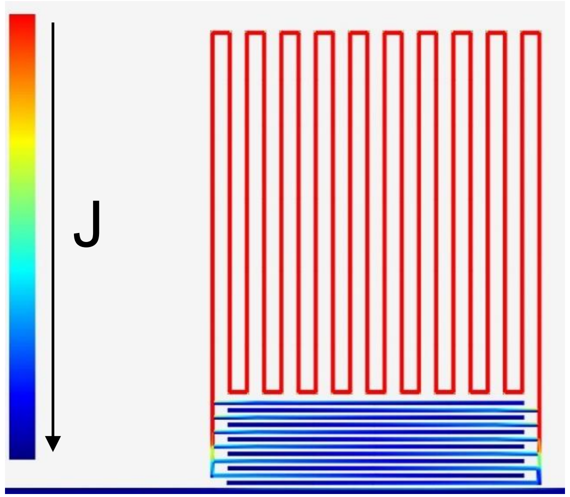
$$n_L \neq n_R \rightarrow \Delta\varphi \rightarrow \theta_f$$

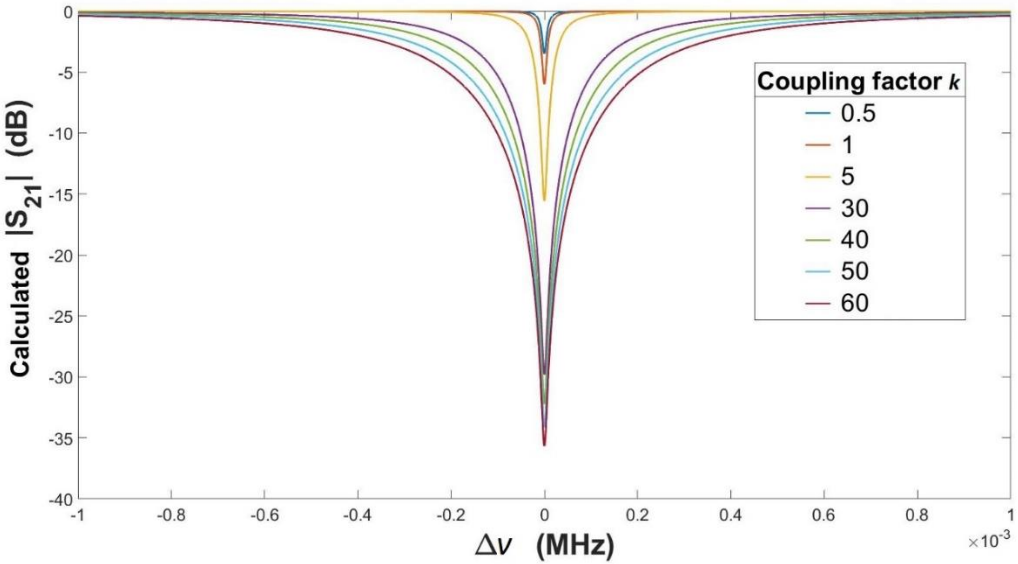
$$\theta_F = \frac{e^3}{2\epsilon_0 m_e^2 c}\frac{1}{\omega^2}\int n_e(z) B_{\|} dz,$$

$$\int n_e(z) B_{\|} dz \approx J.$$

- Polarimetric diagnostic for nuclear fusion plasma
- THz spectral detection range
- Incident power: µW → a few mW
- Cross polarization rejection capabilities, multi-pixel design
- Radiation hardness
- Small footprint
- Reliability → few moving parts

Introduction - Kinetic Inductance Detectors





$$\kappa = \frac{|S_{11,max}|}{|S_{21,min}|} = \frac{1-|S_{21,min}|}{|S_{21,min}|}$$

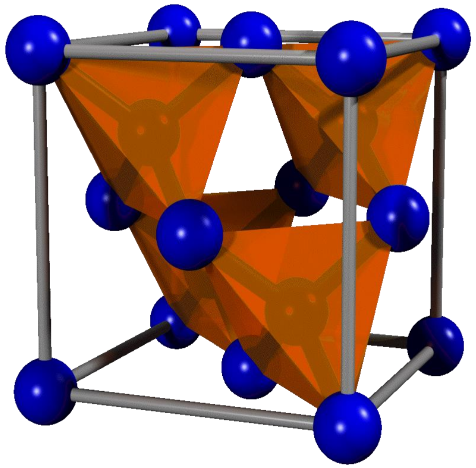
$$Q_L = \frac{\nu_{res}}{\Delta\nu_L}$$

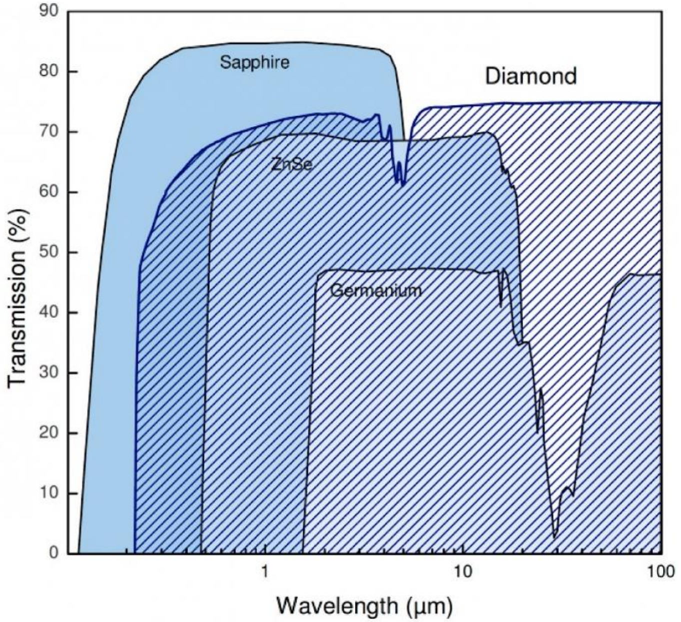
$$Q_0 = Q_L(1+\kappa) = \frac{Q_L}{|S_{21,min}|}$$

$$Q_C = \frac{Q_0}{\kappa} = \frac{Q_L}{1-|S_{21,min}|}$$

- Superconducting (SC) thin film LC micro-resonators
- Photons → Cooper pair breaking → excess e^- → L_K↑ → S_{21} Δω & Δφ
- LEKID: discrete inter digital capacitor (IDC) and inductor → easy freq. tuning (FDM) & inductor uniform current
- Depth and width of the resonances are strongly dependent on coupling *k*
- Design optimization: no saturation & no overlap → evaluation of coupling strength/Q_C
- SC of choice: Niobium Nitride (T_C (bulk) >16 K)

Introduction – Why diamond based detectors?





- Extremely low heat capacity C and extremely high thermal conductivity → fast response (thermal detectors)
- Transparency → no substrate events
- Low losses and low dielectric constant (especially at microwave frequencies) → potential for very high internal quality factor
- Radiation hardness
- Mechanical stability → thin substrates (<20 µm) possible
- High breakdown voltage → no radiation generated charge carriers → transparent at very high radiation intensities.

- Diamond and Related Materials, 3 (1994) 747-751
- IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 3, NO.I, MARCH 1993

Detector design and optimization - simulations

SONNET Software

Analysis: Maxwell's equations, solving for J planar multilayer geometries
Parameters: L_k, ε_r, $\tan(\delta)$

Frequency Tuning

Single pixel analysis, variation of IDC finger numbers and length

Cross Talk Analysis

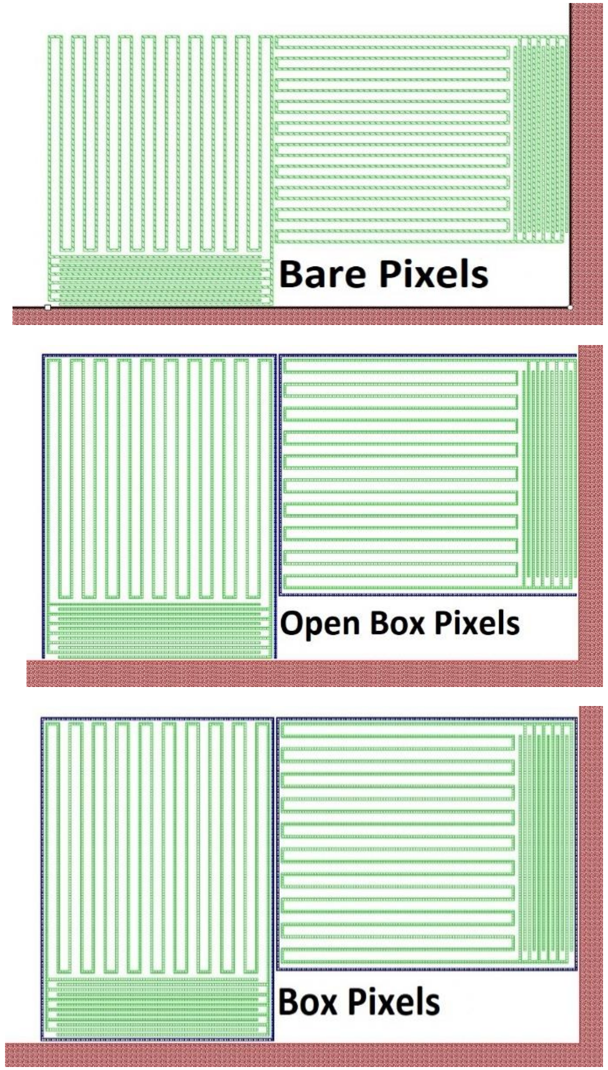
2 identical pixels, bare / box / open box inter-pixel distance variation

Q_c / t-line coupling

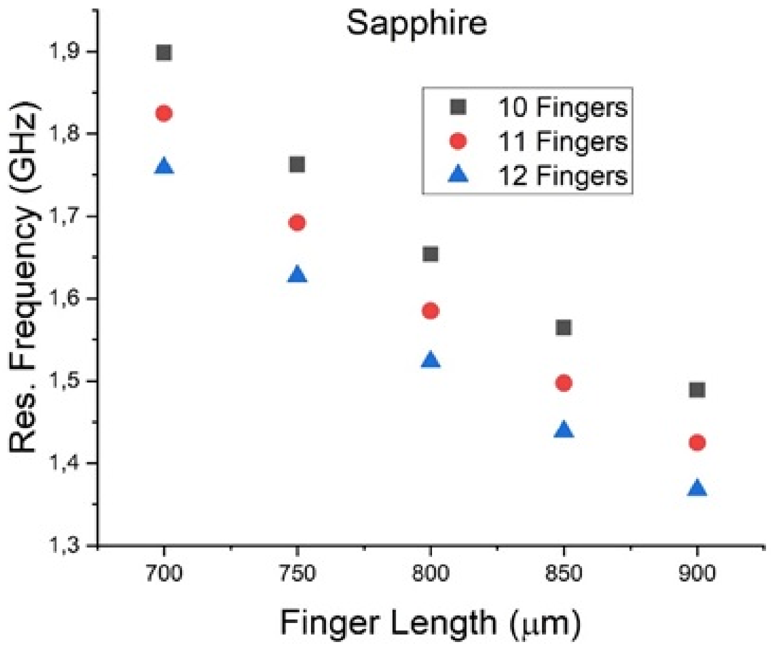
Single pixel, bare / box / open box feedline – pixel distance variation

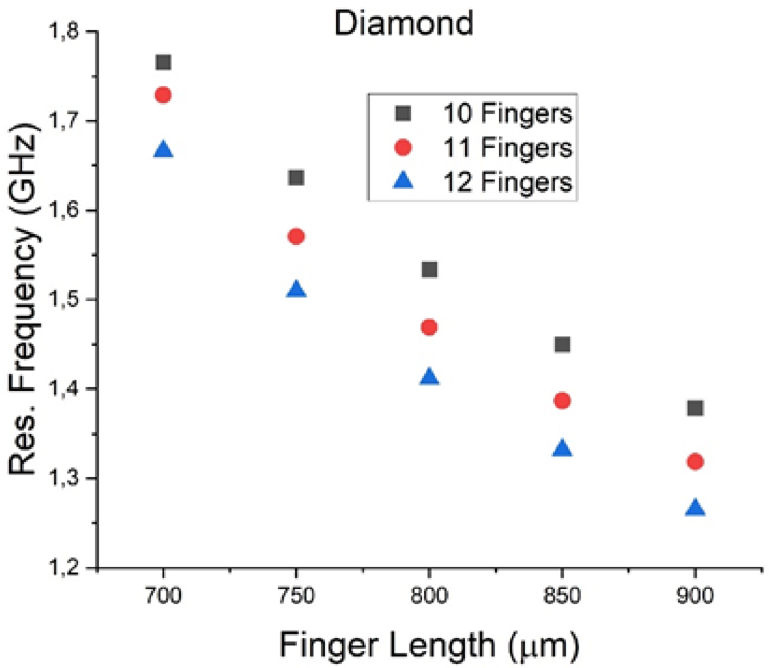
Substrate materials

Silicon (not shown), Sapphire, Diamond (poly)



Frequency Tuning

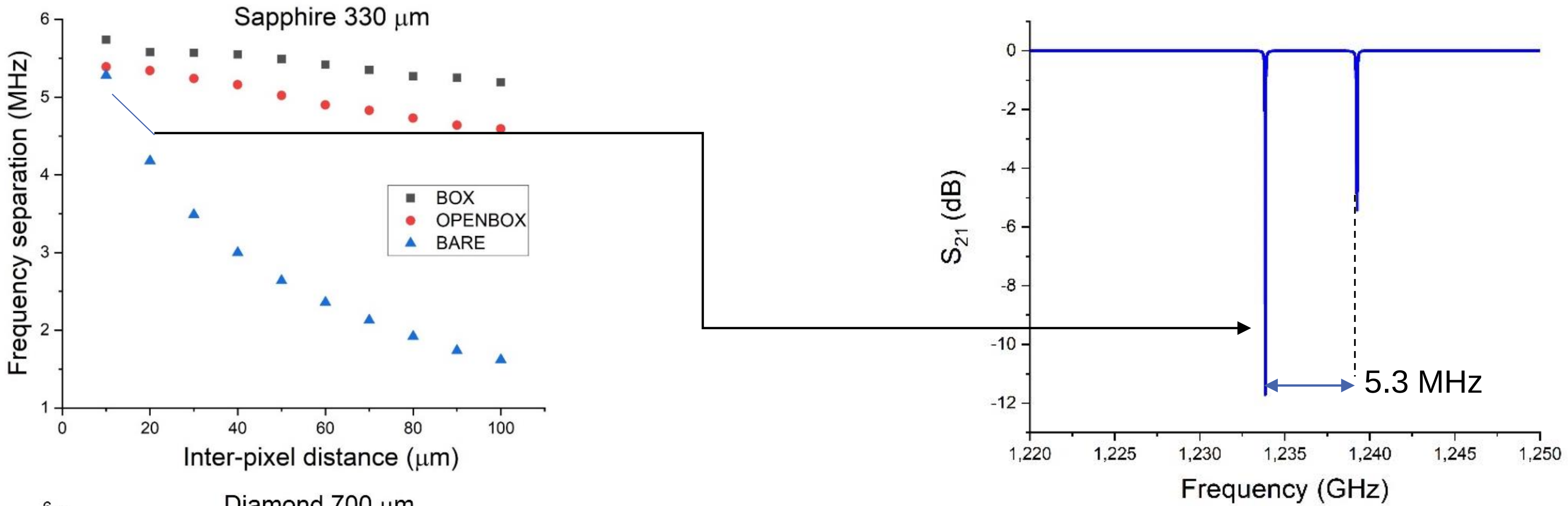


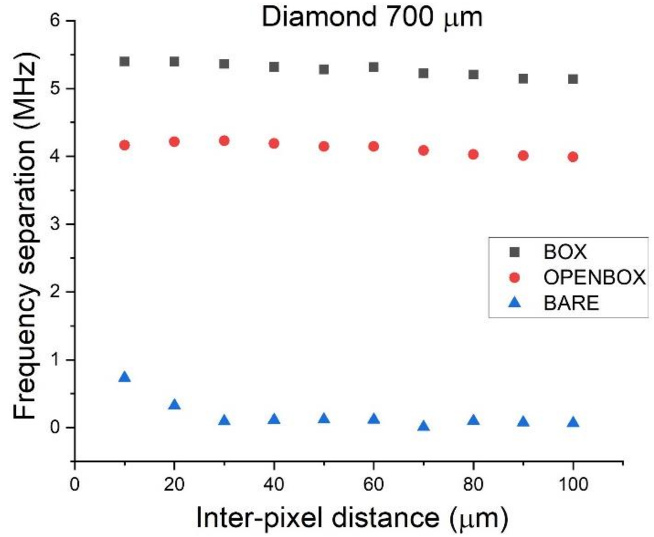


Substrate	Thickness	ε_r	tan(δ)	L_k (NbN)	ν (range)	Δν
Sapphire	330 µm	10.06	$5 \cdot 10^{-6}$	7.28 pH/□	1.35 – 1.9 GHz	36.7 MHz
Diamond	700 µm	5.67	10^{-5}	22.77 pH/□	1.25 – 1.75 GHz	33.3 MHz

- Diamond lower ε_r compensated by thicker substrate → similar frequencies
- 3 different combination of equally spaced resonances selected for production

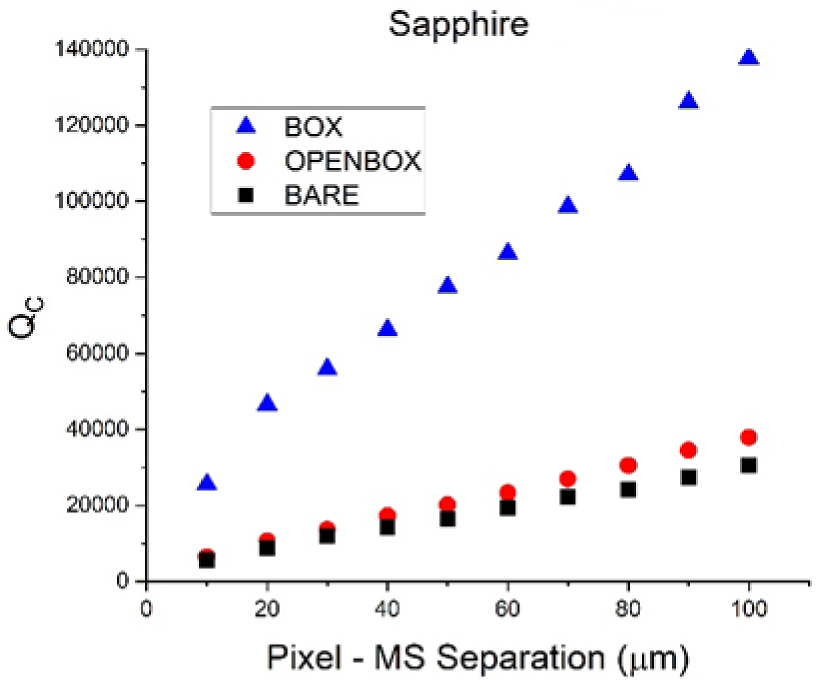
Cross-talk analysis

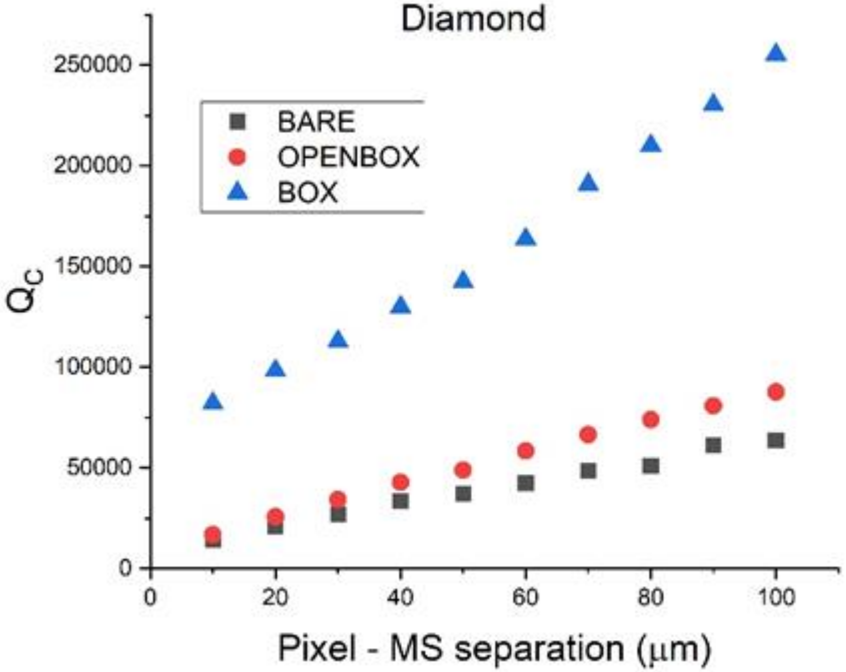




- Larger separation = stronger cross-talk
- Diamond: lower ε_r → smaller cross-talk
- Shielding structures *increase* the cross-talk (contrary to literature reports)
- Tilted 2x2 configuration → ungrounded shields = coupling booster

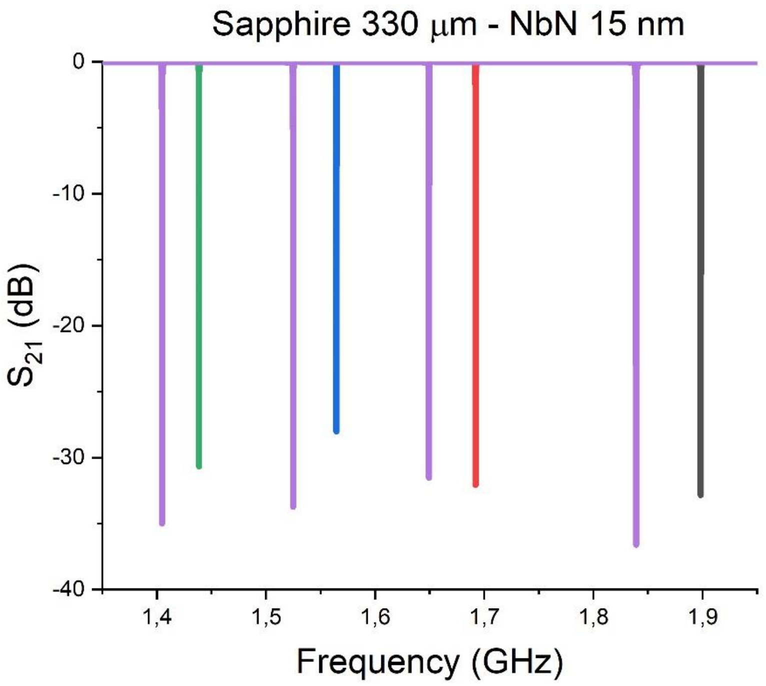
Q_C Evaluation

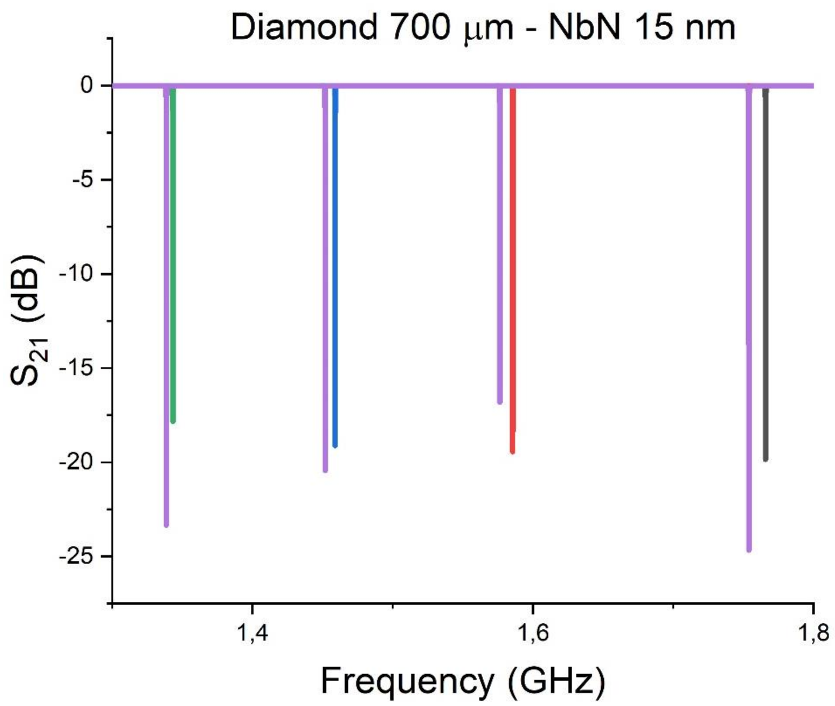




- Power intensive application → prioritize stronger coupling (low Q_C) → deeper resonances, no saturation
- Expected Q_0 under illumination. $\approx 10^3$-10^4 , optimum coupling, max resp: $Q_C = Q_0 = 2Q_L$
- For the same configuration, diamond present lower coupling compared to sapphire
- Fully enclosed shielding pushes the Q_C toward values in the 10^5 range

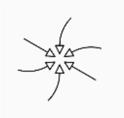
Complete Detector Simulations





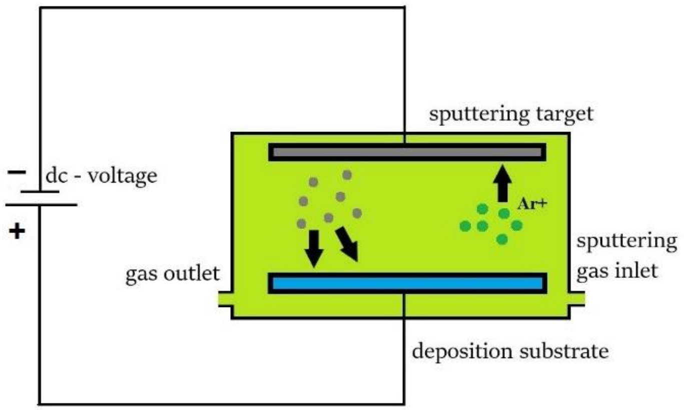
No cross-talk: adjacent pixels sufficiently separated in frequency

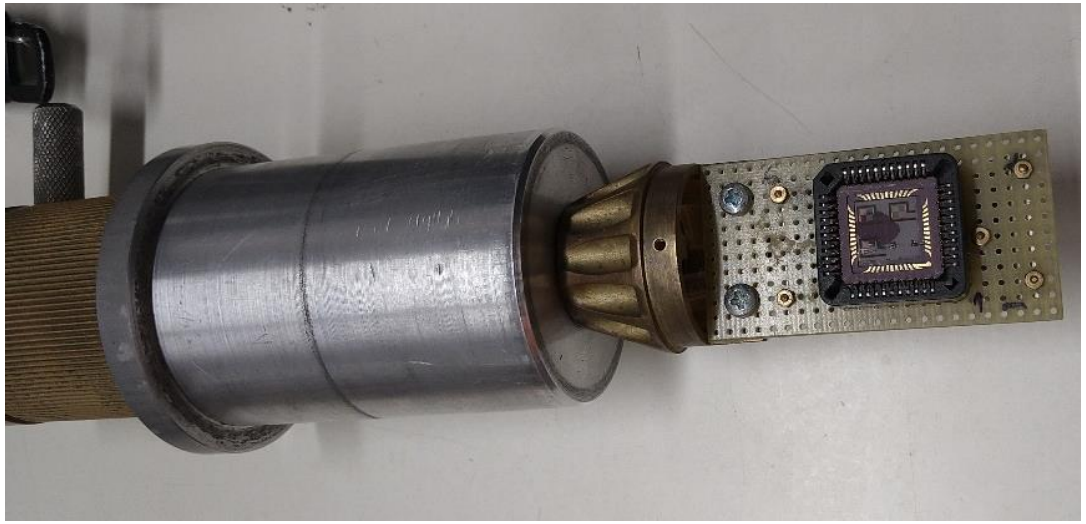
Additional capacitive effects → Detector resonance frequency (purple) lower than single pixels (colored) → low ε_r of diamond greatly limits this effect



Final design: No shielding, 3 Prototypes

Film deposition and characterization





DC reactive magnetron sputtering

- Sub. temp: 850°(Sa), 750° (Di)
- Deposition rate 0.065 nm/s

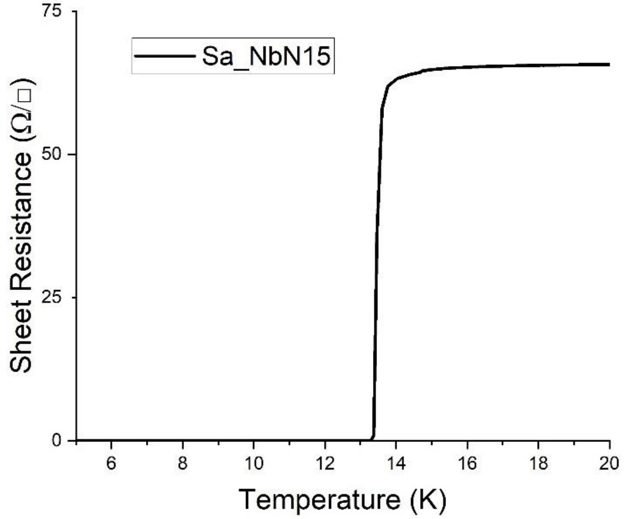
Photolithography and RIE

- Positive tone UV Photolith.
- RIE: 30 sccm SF_6 + 6 sccm O_2

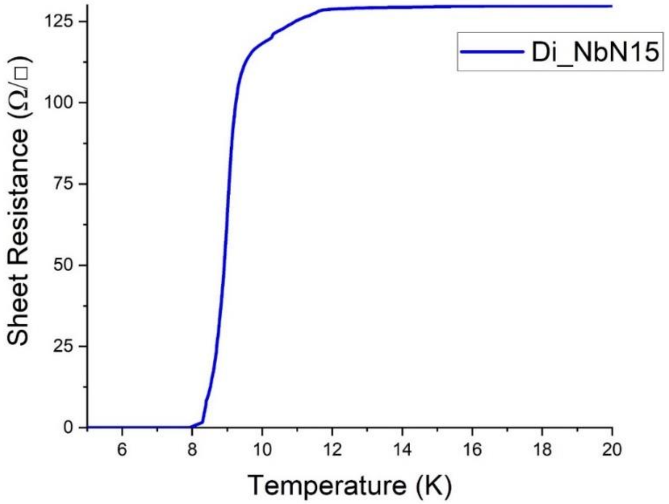
Thin film Characterization

- Multi channel DC dipstick, 4 terminal probing
- R/T curve → $\Delta(T) \approx 1.74 \cdot \Delta(0)\left[1 - \frac{T}{T_C}\right]^{\frac{1}{2}}$, $\Delta(0) = 1.76 \cdot k_B T_C$ → $L_k = \frac{\hbar R_s}{\pi \Delta}$

SC thin film DC characterization



- a = 4.785 Å
- Mismatch: 0.4 Å
- High T_C uniform, sharp transition → high quality

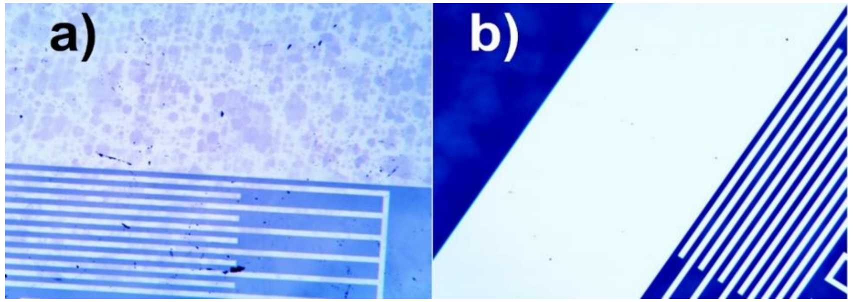


- a = 3.567 Å
- Mismatch: -0.81 Å
- Low T_C, wide ΔT_{C}, multi step, high $R_{\square}$ → lower quality

Sub-Film.	T_C (K)	ΔT_C (K)	R_s ($\Omega_\square$)	Δ (meV)	L_k (pH/$\square$)
Sa-NbN15	13.4	0.18	70.6	2.03	7.28

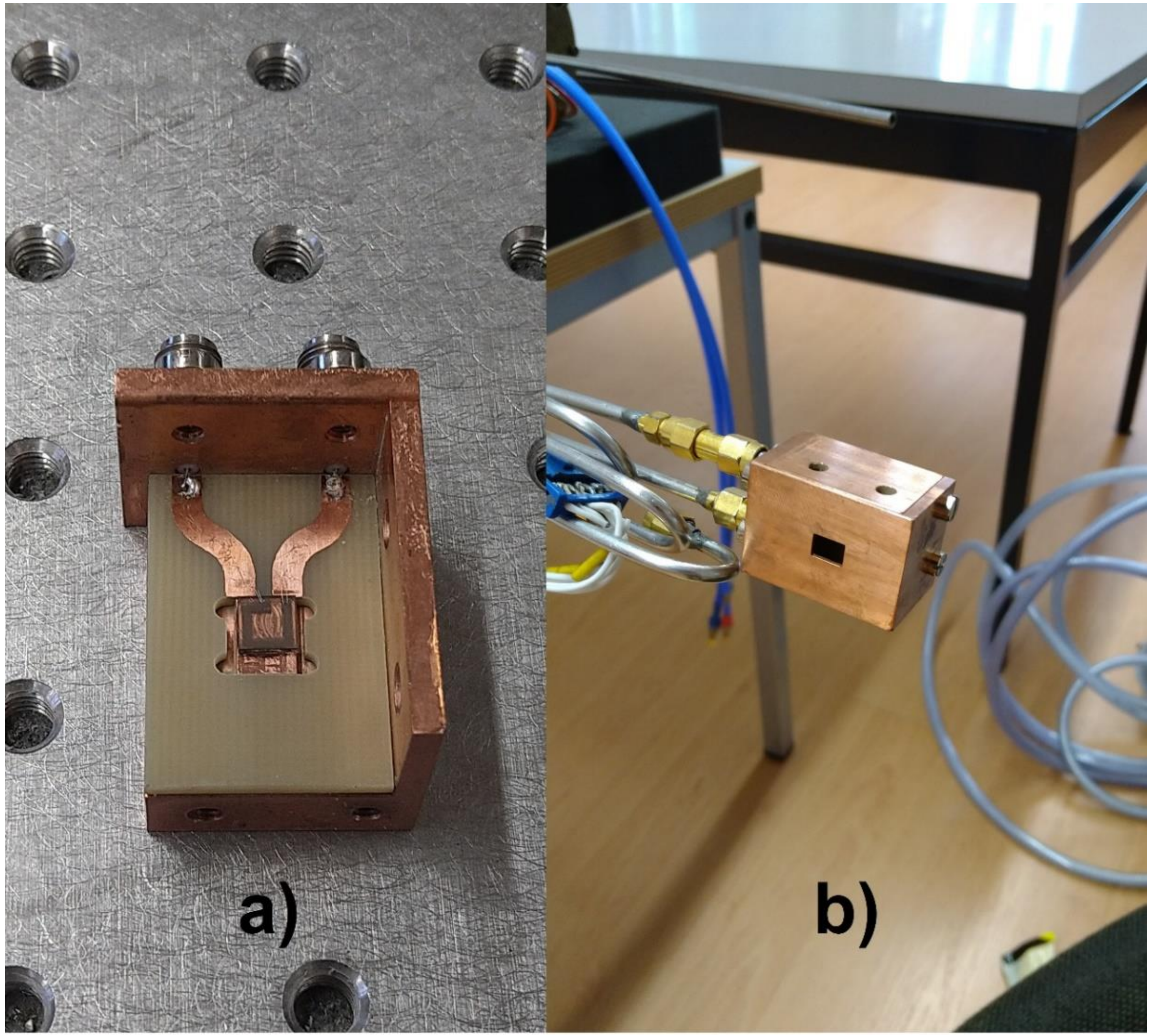
Sub-Film.	T_C (K)	ΔT_C (K)	R_s ($\Omega_\square$)	Δ (meV)	L_k (pH/$\square$)
Di-NbN15	9.05	1.24	156.53	1.44	22.77

- Lattice and CTE mismatch between Di and NbN lead to low quality SC films
- Film degradation apparent under optical microscope, no flaking
- High L_K value for the film on diamond



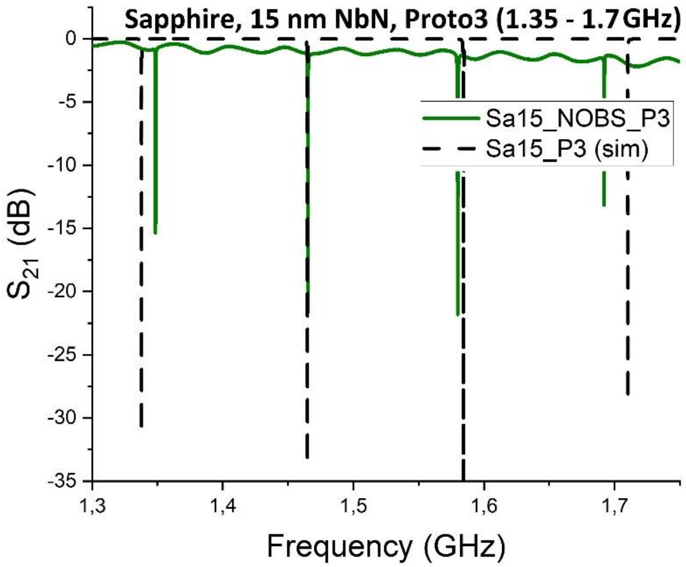
Diamond Sapphire

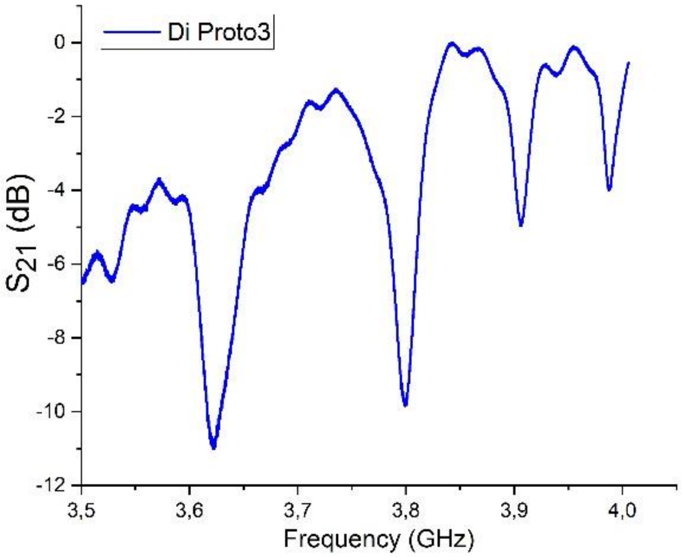
Microwave characterization setup

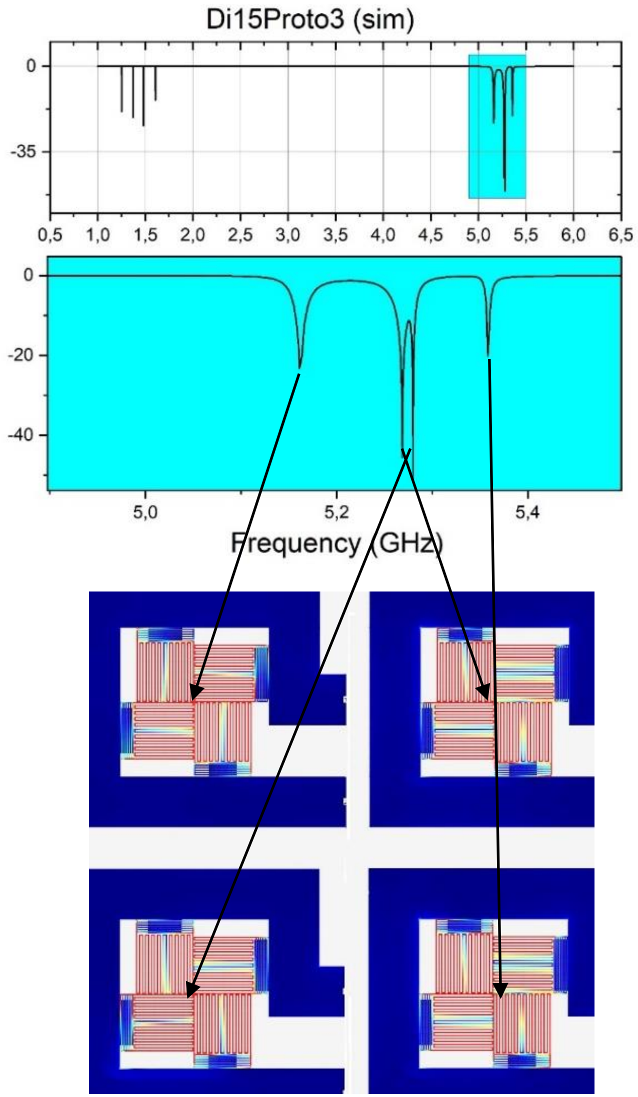


- OFHC Cu detector box + dipstick
- Direct connection with VNA
- -20 dBm injected power + 20 dB attenuator at port1
- Transition to SC marked by -60 → -40 dB baseline jump

Resonance measurements



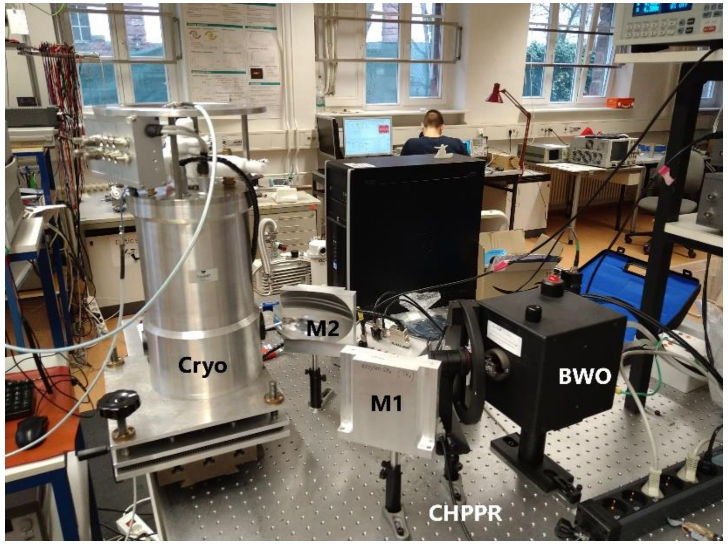


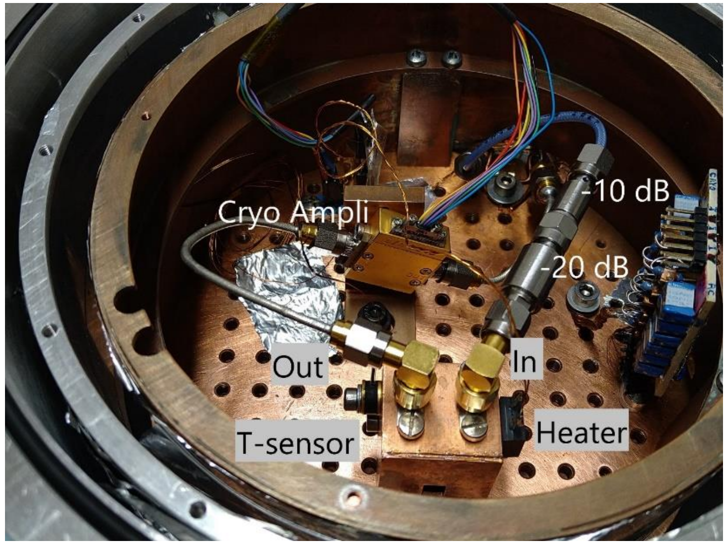


- Deep and sharp resonances
- Measured $Q_C \approx$ 3-5 * 10^3 ~ 2/3 Simulated Q_C
- Simulations ≈ measurements (ΔL_K ~10-15%)

- Simulations: first order (1.25 - 1.55 GHz) + higher order (5.15 - 5.35 GHz)
- Measured: higher order, collective resonances only (3.6 → 4 GHz), Q ~ 10^2
- High resonator internal losses

Detector THz response: measurement setup

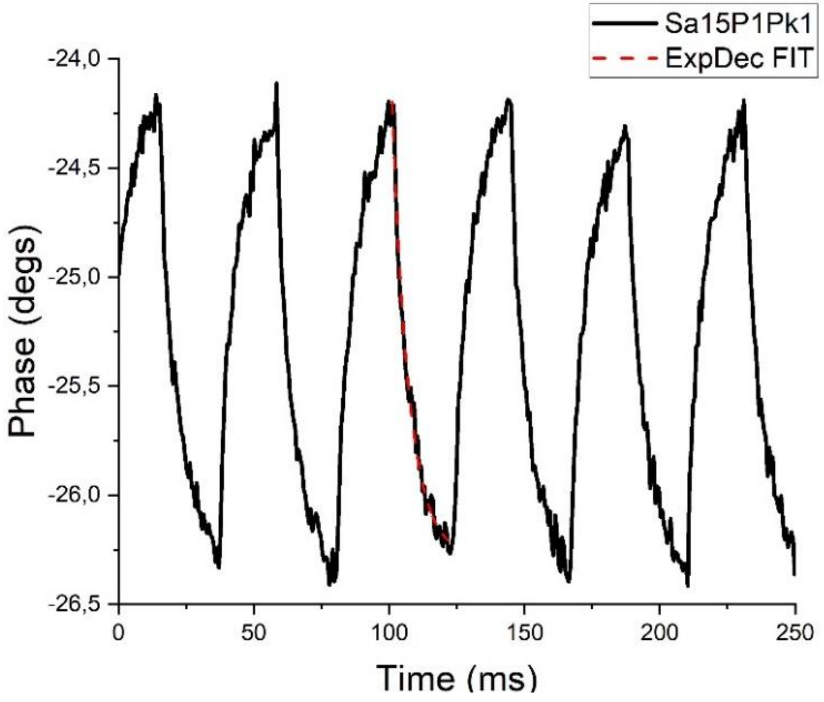




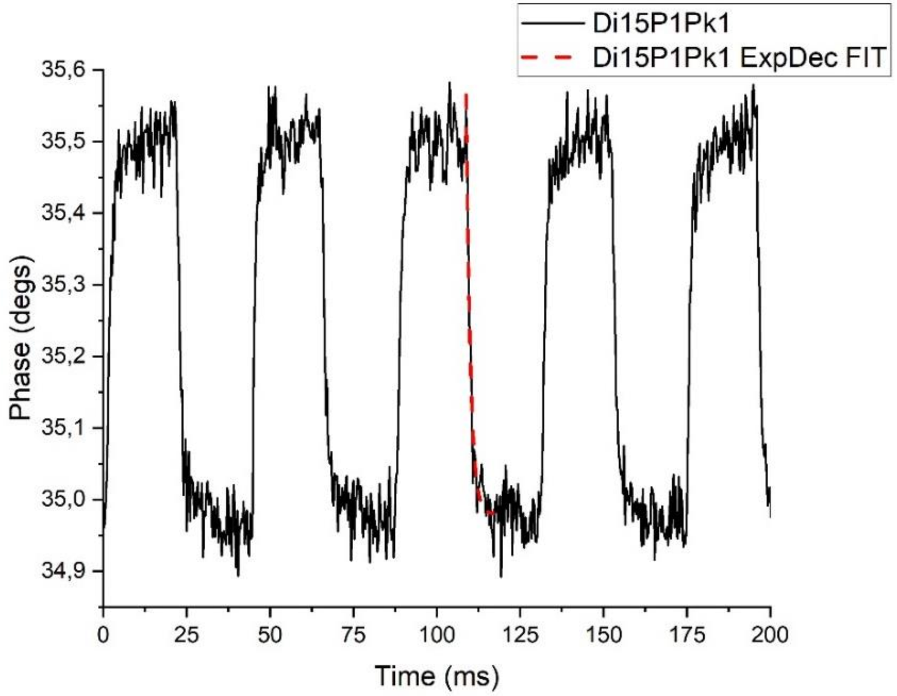
- BWO source @ 900 GHz, 20 μW on detector
- 23 Hz chopper
- LHe bath cryostat

- Detector box with temp. sensor and heater
- 27 dB gain, 1-6 GHz bw cryo amplifier + external RT amplifier
- -10 and -20 dB attenuators

Detector THz response

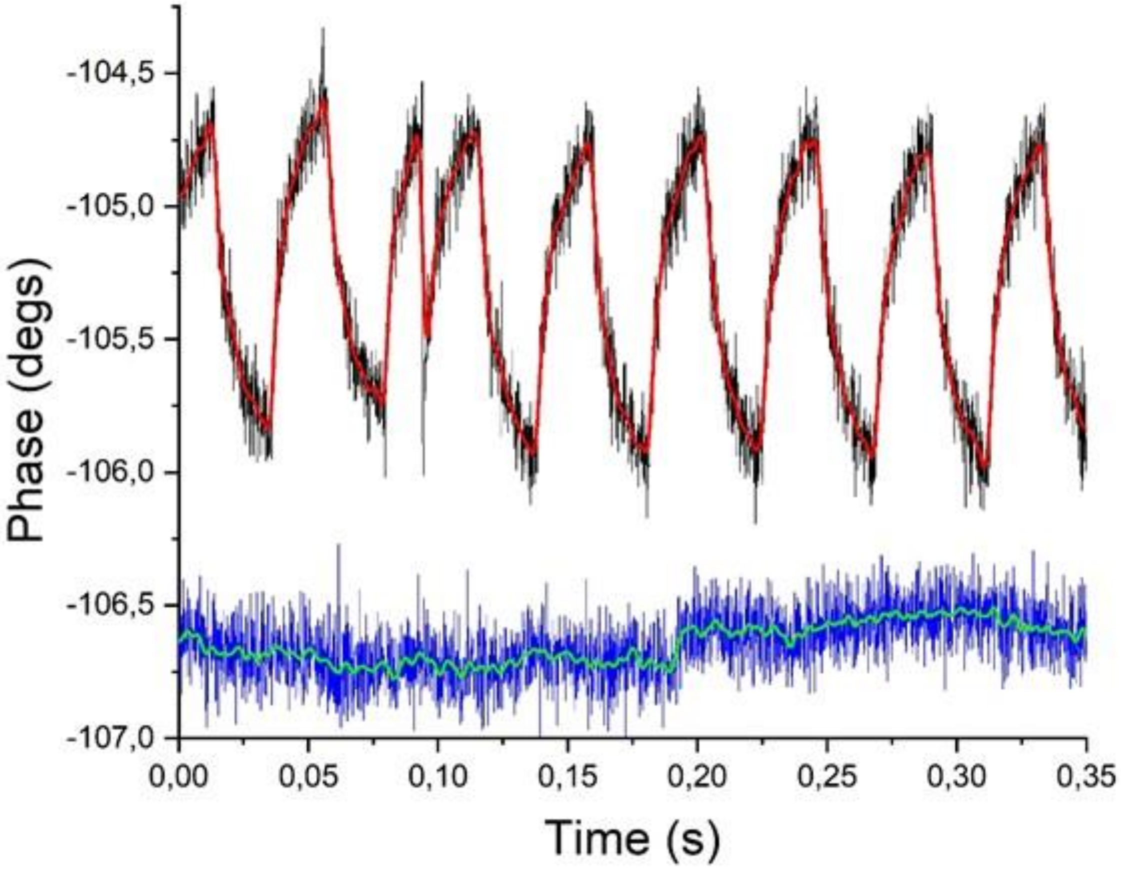


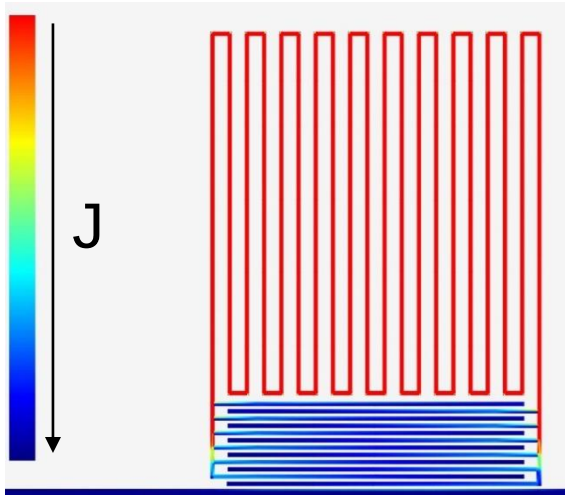
- Measurement Temperature: 4.5 K
- $\tau_{Sa} = 6$ ms → bolometric response
- Responsivity: 0.1 deg./ µW, noise avg. ~ $3*10^{-8}$ W/√Hz (high T + RT ampli)



- Measurement Temperature: 5.5 K
- $\tau_{Di} = 1$ ms → bolometric response, faster dynamics
- Responsivity: 0.03 deg./ µW, noise avg. ~ $3*10^{-8}$ W/√Hz (high T + RT ampli)

Cross polarization rejection

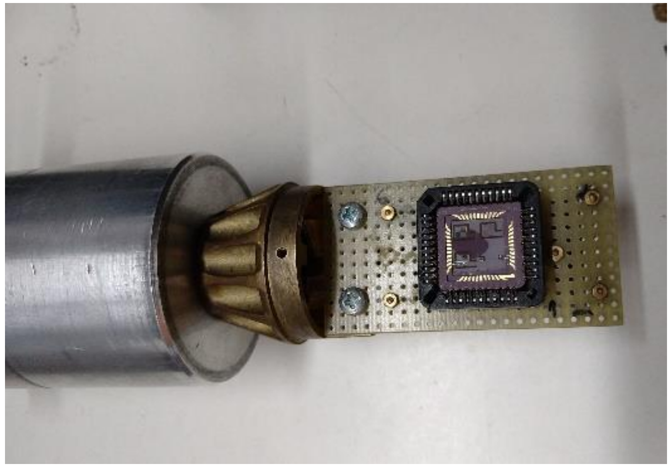


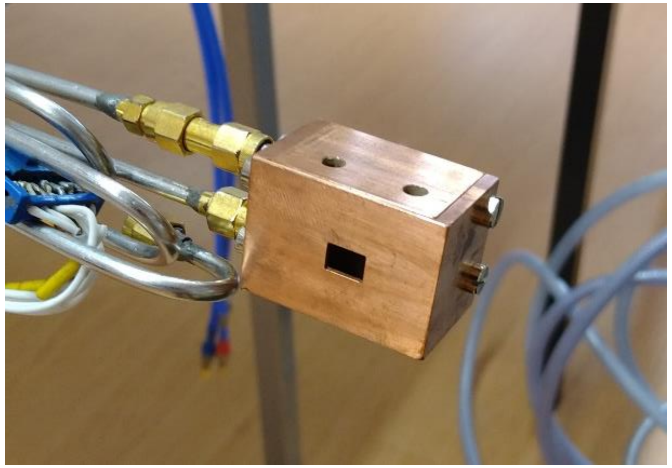


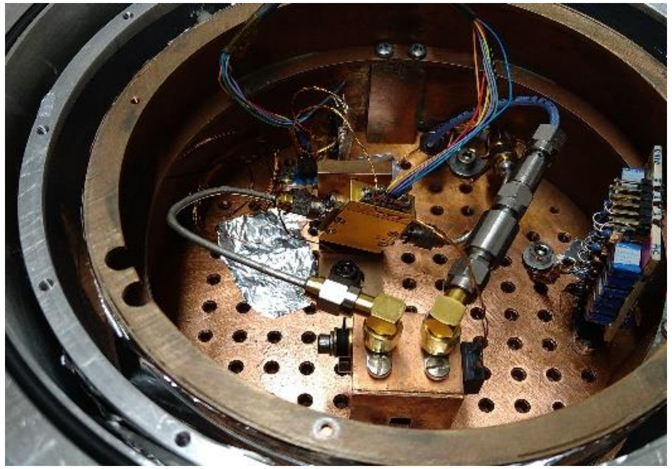
- Polarization selector: waveplate + liner polarizer
- Capacitor contribution negligible (low J)
- Detector design effective in rejecting cross-polarization

Summary

- Polarization sensitive KIDs based on diamond substrates have been studied and developed for fusion plasma applications
- Design finalized through simulation study for multiplexing, cross talking and coupling strength
- NbN films on diamond suffer from low quality, caused by the lattice and CTE mismatch
- Bolometric response, $\tau_{\mathrm{Di}} < \tau_{\mathrm{Sa}}$
- First investigation of diamond as substrate for LTSC detectors → first step toward the optimization of this technology
- Next steps: film quality improvement with AlN buffer layer, single crystalline diamond epitaxial growth on iridium

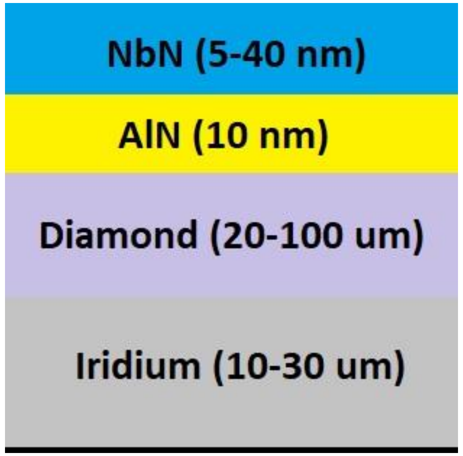






BACKUP

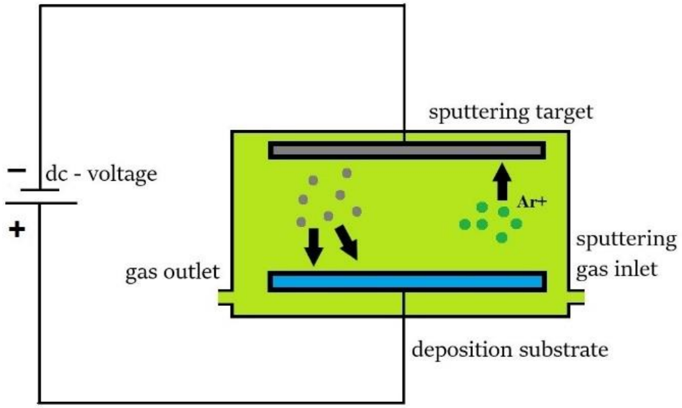
Future outlook - Heteroepitaxial KID

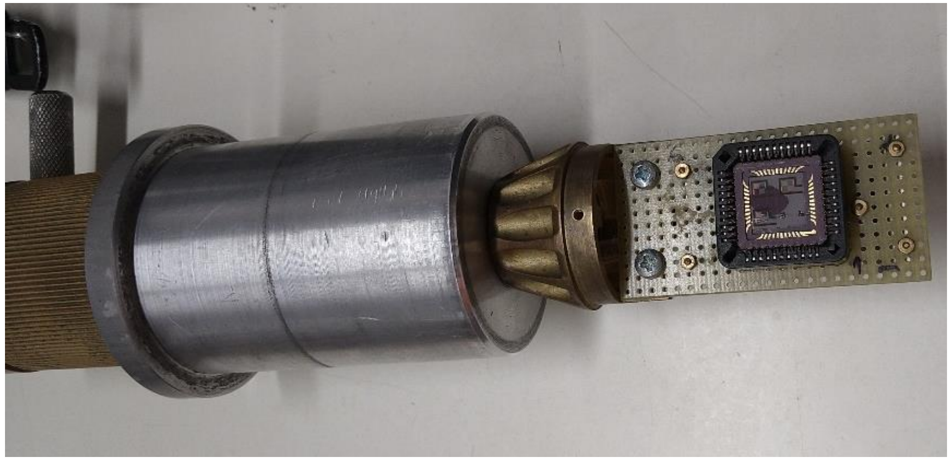


- Iridium is the best substrate for growth of single crystal diamond
- It has the ability to promote single crystal growth even when used as interlayer with a very rough main substrate, with large lattice mismatch.
- The diamond films grown on Ir have highly improved alignment and extremely low mosaicity → above a certain thickness, the films are single cryst.
- MBE and PLD deposition techniques
- Extreme corrosion resistance
- Iridium could additionally work as backshort / ground plane for a microstrip based KID
- AlN buffer layer for increased film quality

- Appl. Phys. Lett. **78**, 192 (2001)
- Appl. Phys. Lett. **91**, 061501 (2007);

Film deposition and characterization





<u>DC reactive magnetron sputtering</u>

- Sub. temp: 850°(Sa), 750° (Di)
- Deposition rate 0.065 nm/s

<u>Photolithography and RIE</u>

- Positive tone UV Photolith.
- RIE: 30 sccm SF_6 + 6 sccm O_2

<u>Thin film Characterization</u>

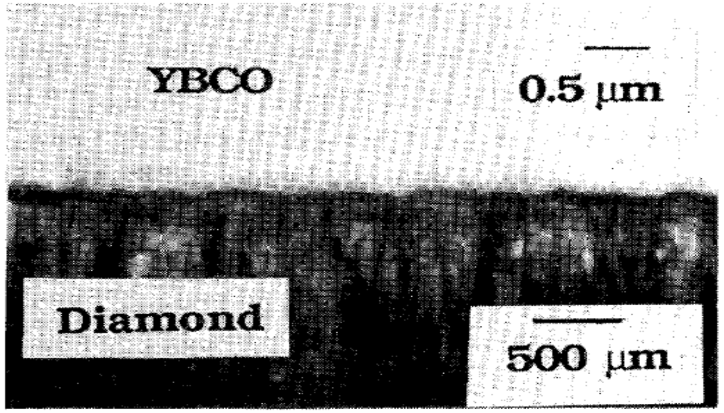
- Multi channel DC dipstick, 4 terminal probing
- R/T curve →

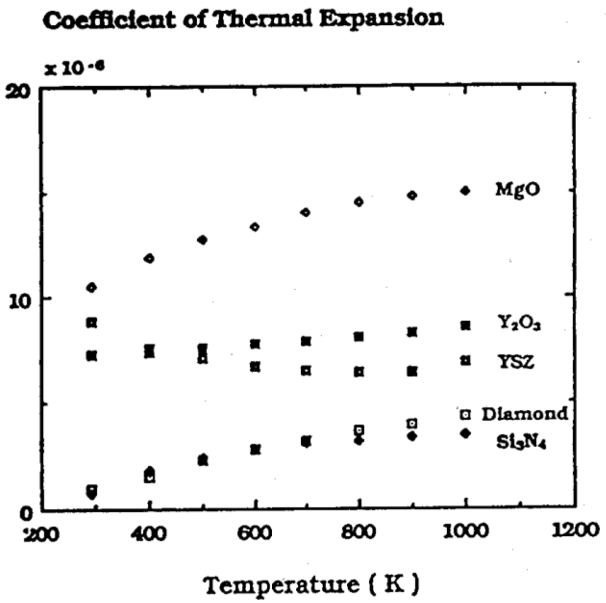
$$\Delta(T) \approx 1.74 \cdot \Delta(0)\left[1 - \frac{T}{T_C}\right]^{\frac{1}{2}}$$

$$\Delta(0) = 1.76 \cdot k_B T_C$$

$$\rightarrow L_k = \frac{\hbar R_s}{\pi \Delta}$$

YBCO Deposition on diamond





YBCO can be directly grown on poly-Di, but

- Very low quality film (T_C = 17K)
- Very difficult patterning
- No sharp separation of layers of SC and sub.

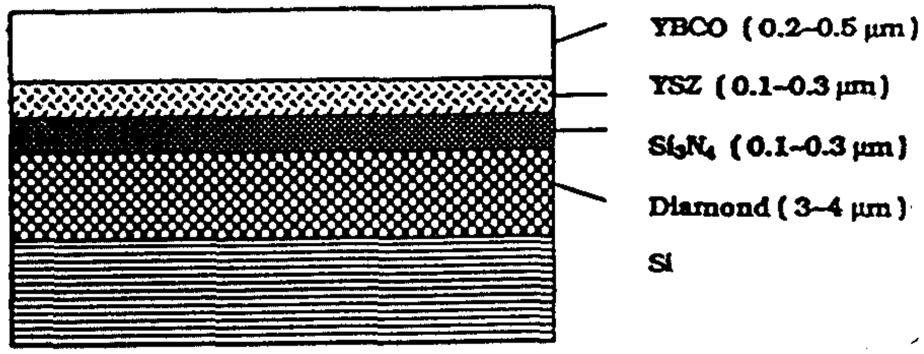
YBCO deposition is an O_2 dependent process → decomposition of Di

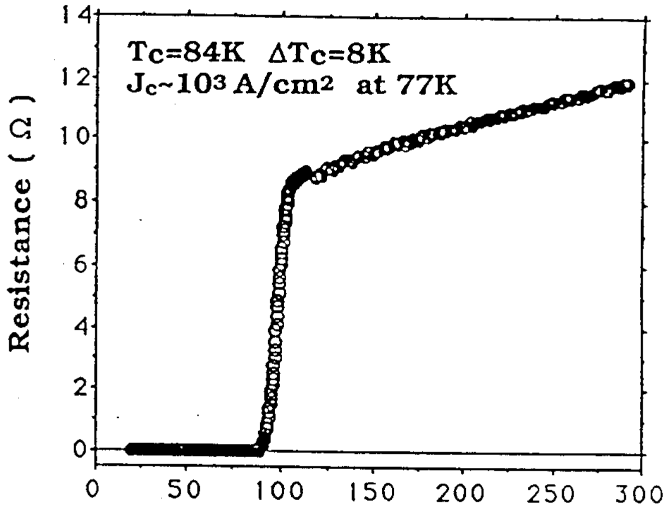
→ Si_3N_4 / YSZ Buffer layer system

- Coefficient of thermal expansion (CTE) and lattice matching → avoid film cool down cracking
- Yittrium Stabilized Zirconia: growth template for Di nucleation
- Si_3N_4 acts as a barrier for the diffusion of oxygen and carbon, protects Di during YBCO depo.

"M. Ece et al. / Superconducting films on diamond by PLD"

YBCO Deposition on diamond - state of the art films

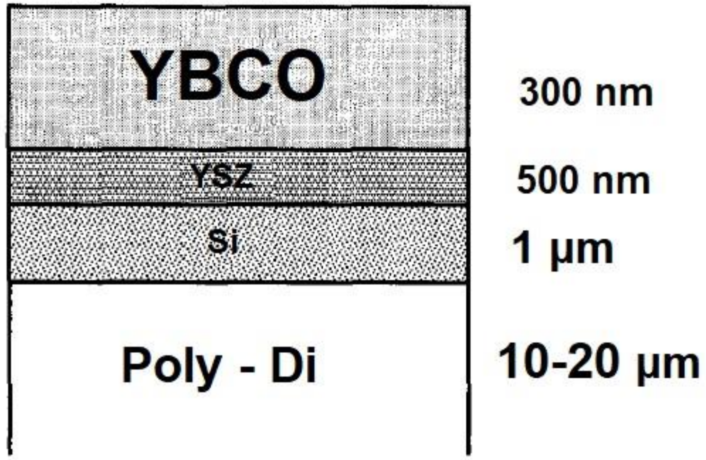


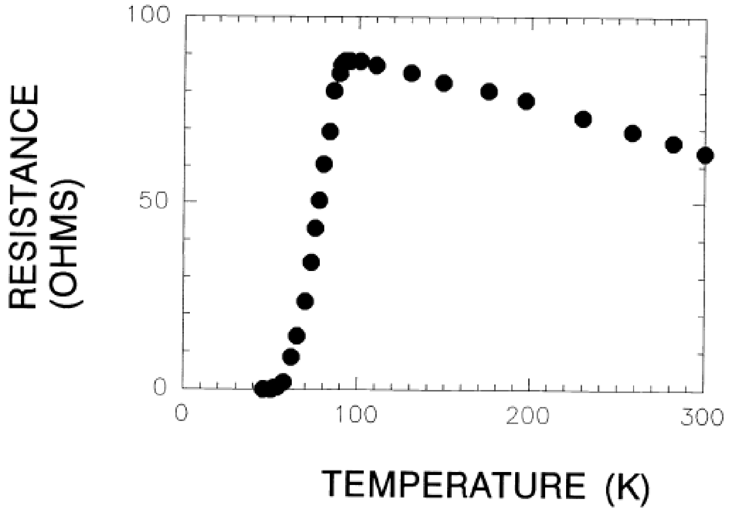


- 2-4 μm thick nanocrystalline (< 0.2 μm) diamond films, 500-1000 Å roughness, over Si wafers.
- Pre-annealing of diamond films at 680-800 C for 1-3 hours in high vacuum (2.6×10^{-6} Torr) – outgassing of H from diamond
- 0.1 – 0.3 μm Si_3N_4 deposited by RF-magnetron in 10-20 Torr of Ar @ 680-750 C
- 0.1 – 0.3 μm YSZ deposited by reactive RF-magnetron @ 680-750 C, in 10-30 Torr of mixed Ar/O_2
- YBCO grown in-situ, off-axis reactive RF magnetron @ 660-750 C, in 200-300 mTorr of mixed Ar/O_2
- In situ post deposition annealing, with O_2 venting (600-760 Torr), 30 min @ 500 C
- $T_C = 84$ K, $\Delta T_C = 8$ K, $J_C \sim 10^3$ A/cm^2

"IEEE TRANSACTIONS **ON** APPLIED SUPERCONDUCTIVITY, VOL. 3, NO.l, MARCH 1993"

YBCO Deposition on diamond – lower quality example





- Si/YSZ buffer layer (polycrystalline)
- Plasma CVD deposition of 1 µm amorphous Si layer, vacuum annealing @ 700 C for crystallization
- YSZ and YBCO deposited by laser ablation, 650 C sub. temp., 200 mTorr O_2
- $T_{C\text{-zero}}$ = 50 K, onset = 87 K → 25 K wide transition, low responsivity
- 200x200 μm^2 bolometric micro-bridge, direct laser writing
- 18 V/W responsivity, 6.3×10^{-9} $W^{1/2}$/Hz NEP

“Superconducting YBa2Cu3O7 bolometer on polycrystalline diamond," Proc. SPIE 2159, High-Temperature Superconducting Detectors: Bolometric and Nonbolometric, (20 May 1994)”