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Vacuum gap micro strip microwave resonators for 2.5D integration in quantum computing

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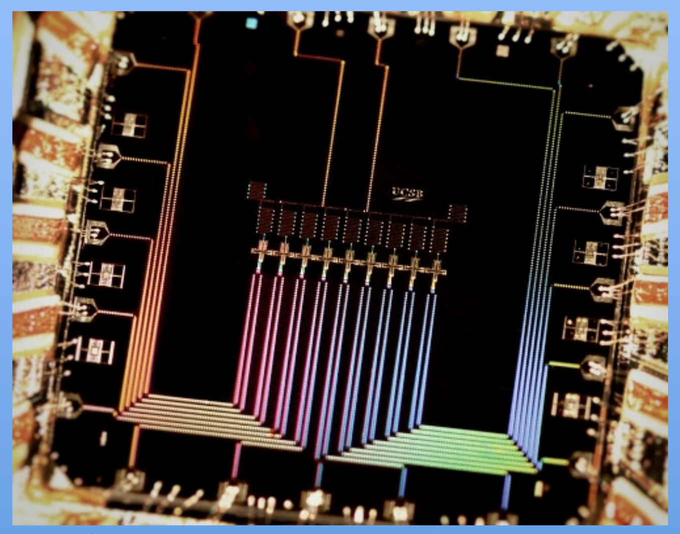
Superconducting qubits show promise; but error correction and larger system sizes demand 2D tiling

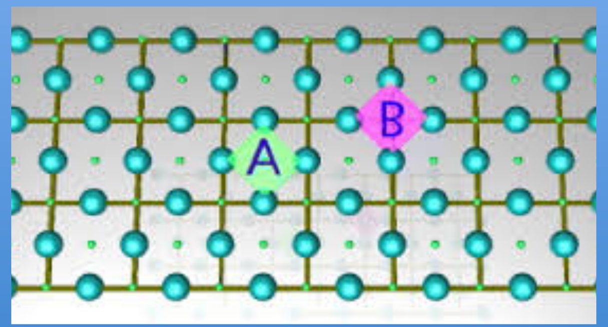


Picture from: 'State preservation by repetitive error detection in a superconducting quantum circuit' J. Kelly *et al.* Nature 519, 66-69 (2015) [1].

Pros:
- Largest solid sate qubit system—nine so far—with room for more
- High fidelity gates
- Enhanced state preservation

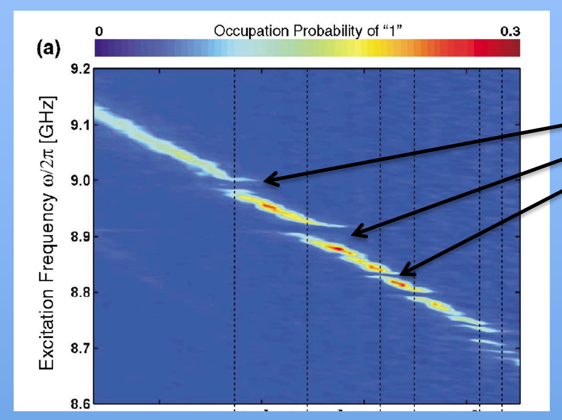
Cons:
- Doesn't scale in 2D
- Limited room for control wiring

Surface code tiling requires 2D



Ref. [2]

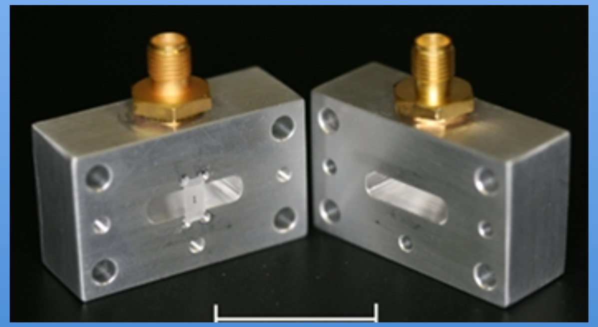
T_1 losses in amorphous insulators prohibit cross-over wiring



Bias current
from R. W. Simmonds et al. [3].

Spectral splittings caused by two-level systems (TLS) states in the insulator

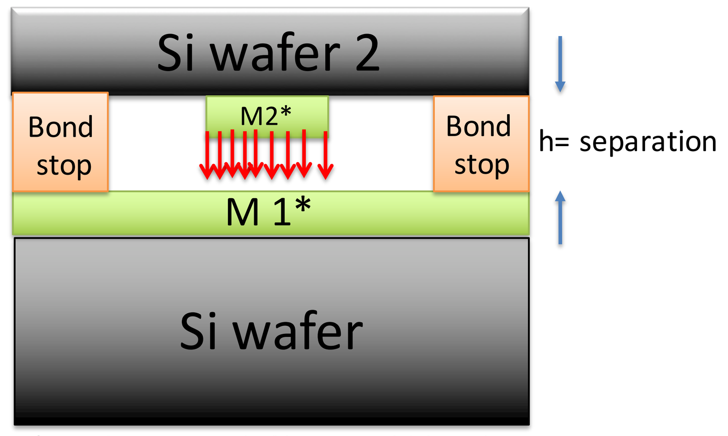
Qubit community has retreated to a minimalist approach to avoid TLSs



Ref. Paik et al. [4]

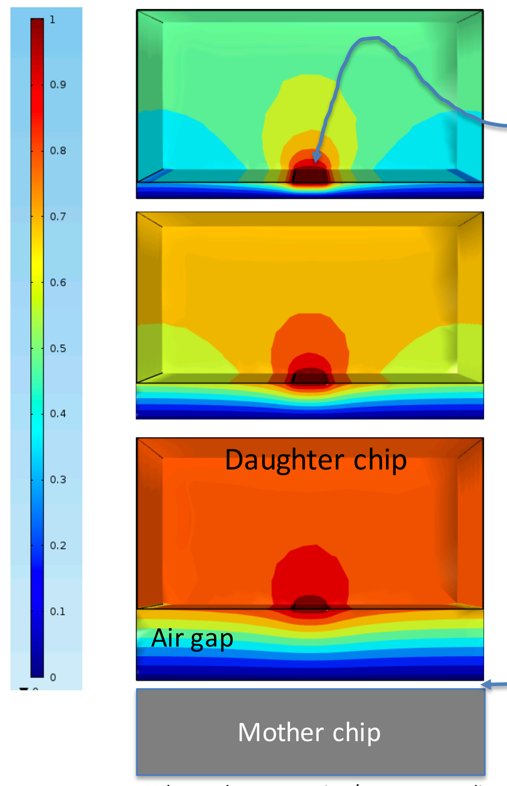
Vacuum gap micro-strip moves electric fields out of dielectrics—demonstrates scalable architecture

(Flip-chip cross section view)



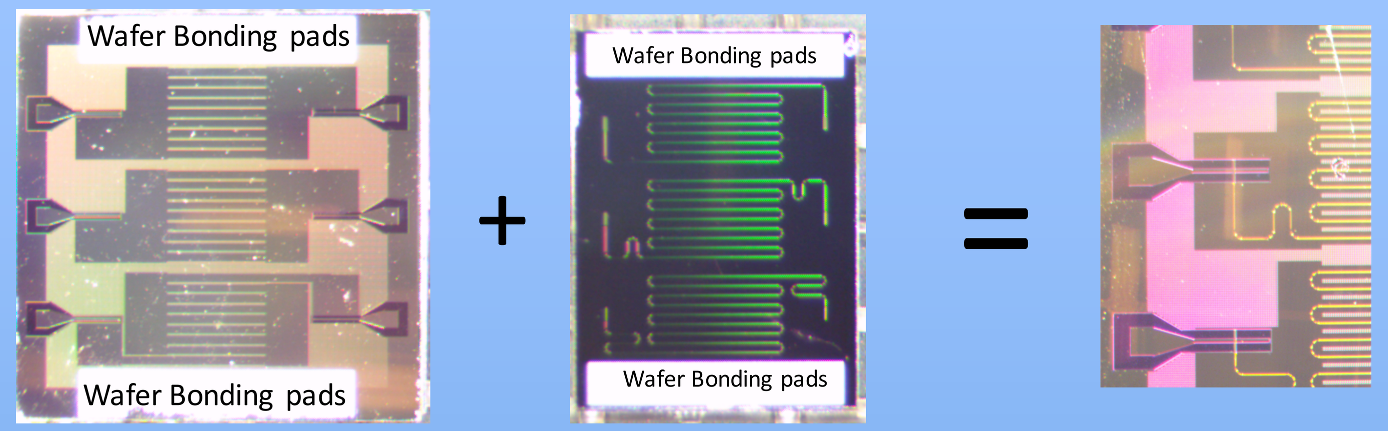
*M1 &M2 are Nb films, could be Al

Electric fields are mostly in air gap for h/w > 1



Where: h = separation/vacuum gap dimension and w = width of the micro strip line

Wafer bonded vacuum gap resonator chips



Mother chip with microwave feed lines | Daughter chip with resonant lines | Combined chip

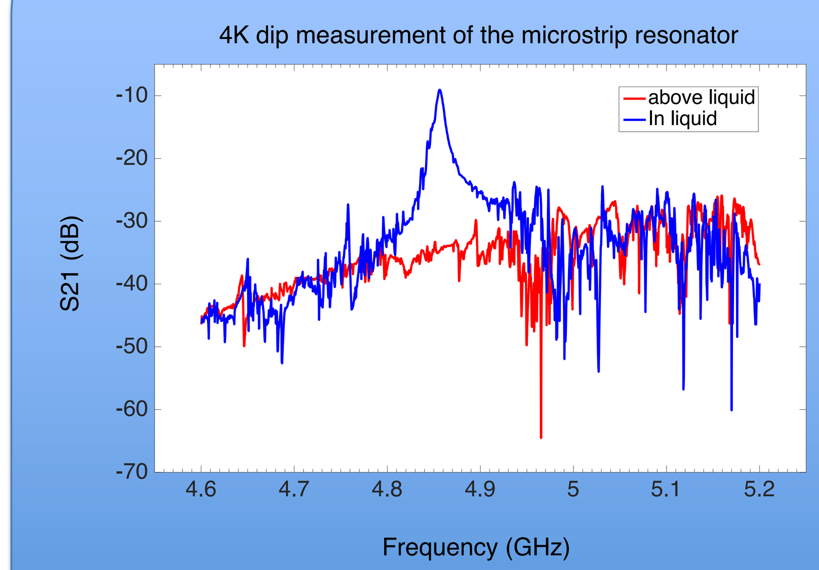
- Three λ/2 microwave resonators of lengths ~ 22mm 23.3 mm, & 24mm per chip. Line is 5 microns wide, vacuum separation ~1 um.
- Coupling caps are parallel plate, 34 um by 10, 20 and 34 um

Eutectic wafer bonding (several recipes)
- Used Sn-In eutectic bond @ 160-170C

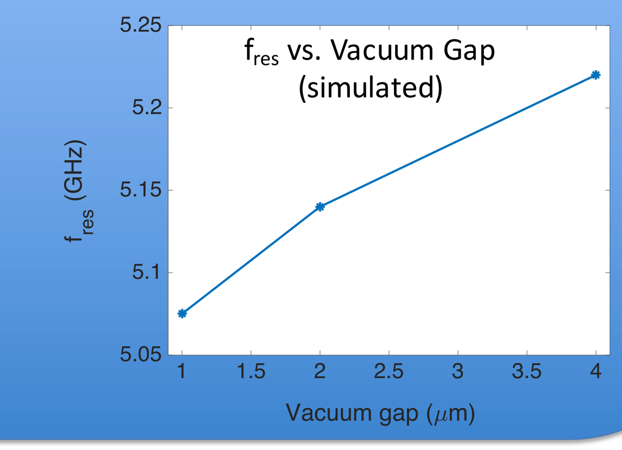
Eutectic Alloy	Eutectic Comp.	Eutectic Temp	Bond Temp*	SLID/TLP
Au-In	0.6/99.4 wt%	156C	180-210C	Yes
Cu-Sn	5/95 wt%	231C	240-270C	Yes
Au-Sn	80/20 wt%	280C	280-310C	Yes
Au-Ge	28/72 wt%	361C	380-400C	No
Au-Si	97.1/2.9 wt%	363C	390-415C	No
Al-Ge	49/51 wt%	419C	430-450C	No

Ok for Al/AlOx JJ!

Measured microwave transmission



- Measured at 4 K in helium
- f_{res} =4.857 GHz matches simulations well



Discussion:

- Demonstrated additional wiring layer for coherent structures
- Minimize substrate participation
- Capacitive coupling for AC structures such as resonators
- Inductive coupling for DC structures, biasing circuits… or bump bonds
- Measurements agree with simulations
- Add through chip vias as low coherence structures for control wiring

See Also:

Publications by T. Brecht et al., ref.[6]

References:

1. J. Kelly *et al.*, 'State preservation by repetitive error detection in a superconducting quantum circuit', Nature 519, 66-69 (2015).
2. Austin G. Fowler, Matteo Mariantoni, John M. Martinis, Andrew N. Cleland, *'Surface codes: Towards practical large-scale quantum computation'*, PRA 86, 032324 (2012).
3. R.W. Simmonds, K.M. Lang, D.A. Hite, D.P. Pappas, J.M. Martinis, 'Decoherence in Josephson phase qubits from junction resonators', Phys. Rev. Lett. 93, 077003 (2004).
4. Hanhee Paik, D. I. Schuster, Lev S. Bishop, G. Kirchmair, G.Catelani, A. P. Sears, B. R. Johnson, M. J. Reagor, L. Frunzio, L. Glazman, S. M. Girvin, M. H. Devoret, and R. J. Schoelkopf, *'Observation of high coherence in Josephson junction qubits measured in a three-dimensional circuit QED architecture,'* Phys. Rev. Lett. 107, 240501 (2011).
5. In-Sn wafer bonding: Yoo, G. & Park, J., *'Sub 200 °C fluxless indium-tin (In-Sn) eutectic bonding for monolithic 3D-IC'*, Journal of the Korean Physical Society (2014) 65: 960. doi:10.3938/jkps.65.960.
6. T. Brecht et al., *'Demonstration of superconducting micromachined cavities'*, Appl. Phys. Lett., 107, 192603; T. Brecht,et al., *'Multilayer microwave integrated quantum circuits for scalable quantum computing'*, NPJ Quantum Information, 2, 16002 (2016).

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