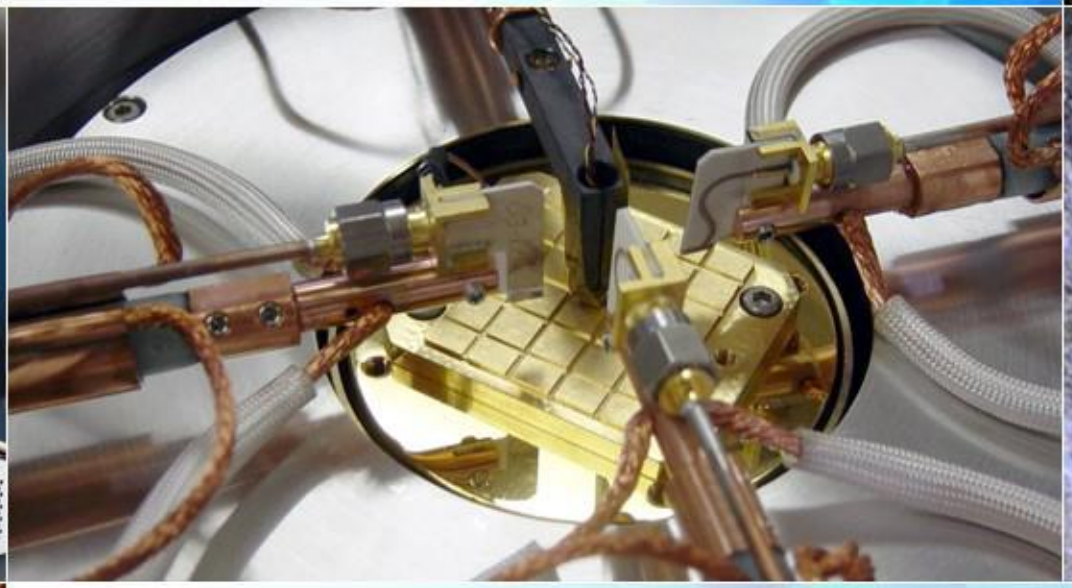
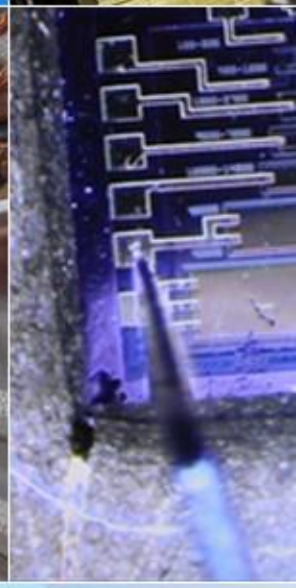
Lake Shore CRYOTRONICS





A Short Guide to Cryogenic Probing & Transport Measurements

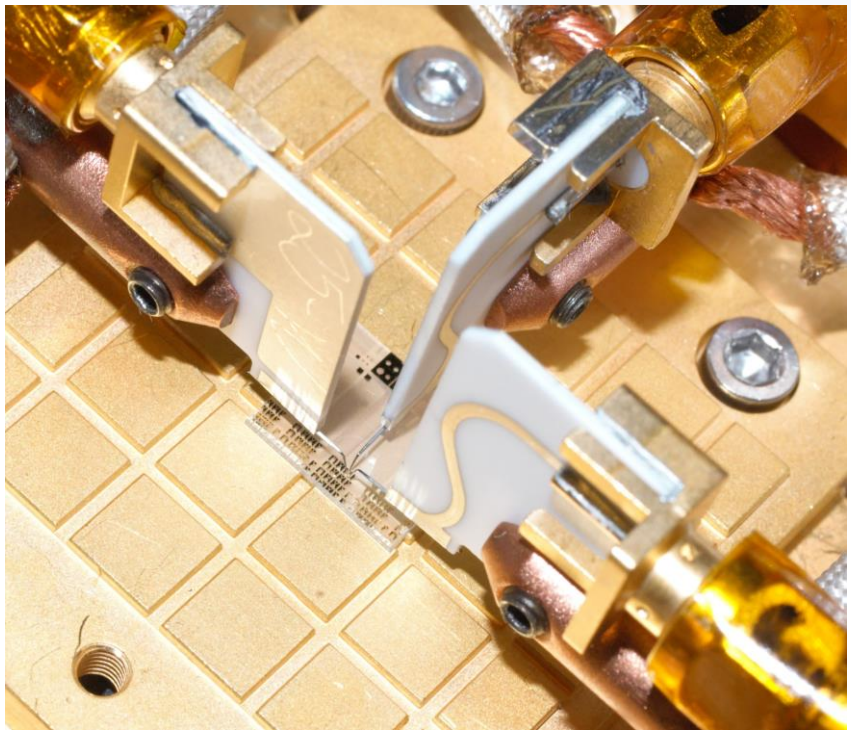
David R. Daughton, PhD
Applications Scientist

Why probing?

Flexible electrical measurement platform enabling:

- Wafer-level characterization (avoid time and cost of packaging)

Manual probe stations ideal for research-scale characterization



Why probing?

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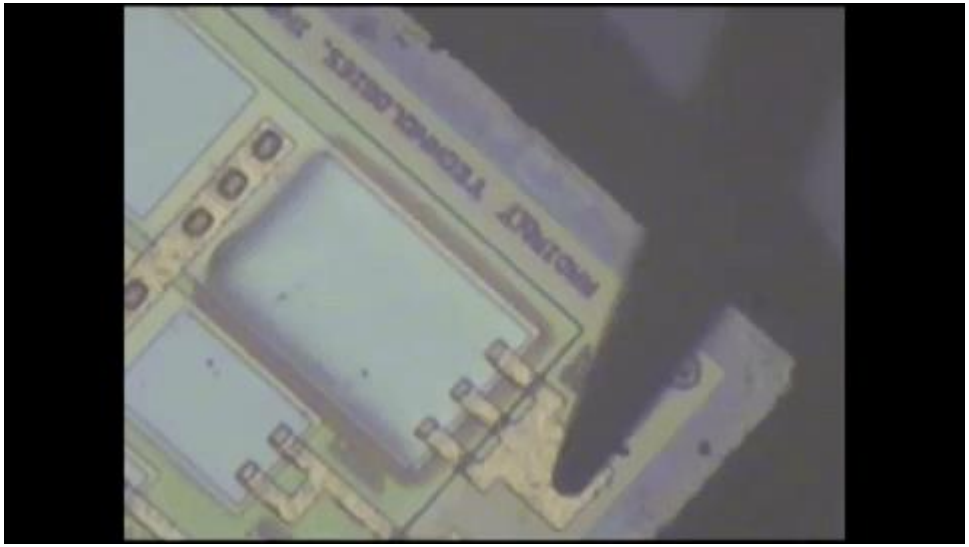
- Device visualization



"Rapidly Characterize Ferroelectric Devices over Variable Temperatures"
Lake Shore Application Note, www.lakeshore.com

Lake Shore CRYOTRONICS

Why probing?

Flexible electrical measurement platform enabling:

- Wafer-level characterization
  (avoid packaging)
- Device visualization
- Environmental control
  (atmosphere, temperature, field, light,…)

Range of platforms

Cryogen-Free Probe Stations

Cryogenic Probe Stations

Horizontal Field

Vertical Field

No Field

Lake Shore CRYOTRONICS

Anatomy of a cryogenic probe station

Sample stage

Anatomy of a cryogenic probe station

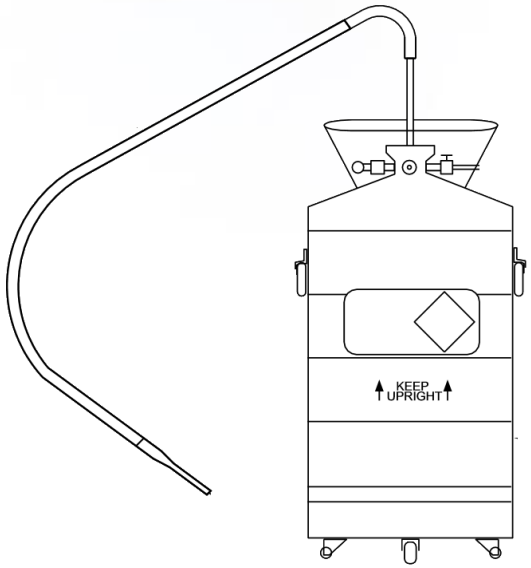
Sample stage

Gifford-McMahon (GM) cooler
- No liquid cryogens
- “Closed-cycle” system

Lake Shore CRYOTRONICS

Anatomy of a cryogenic probe station

Sample stage



Liquid helium or nitrogen

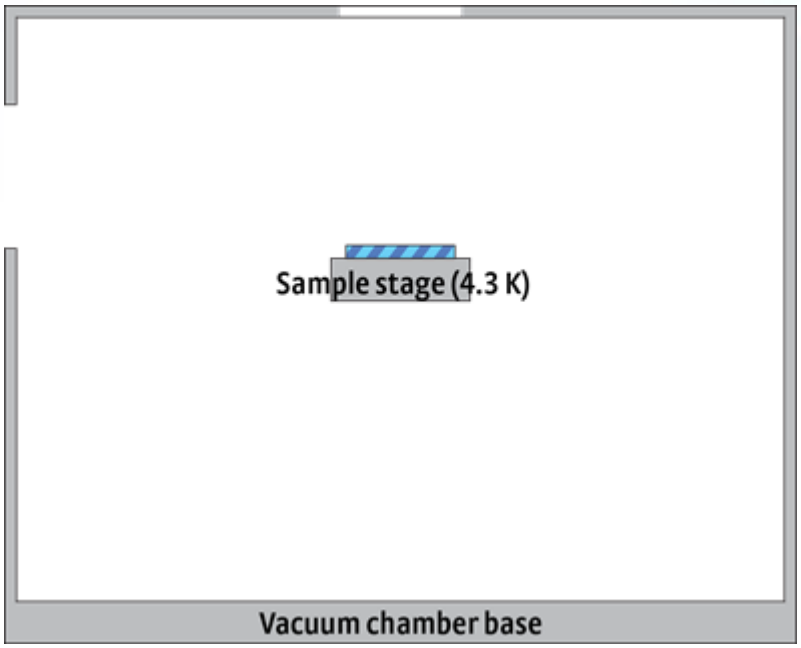
- “Wet” system
- Often lowest vibrations
- Faster cycle times

Anatomy of a cryogenic probe station

Vacuum chamber

Prevents gas adsorbates freezing to surface of wafer

- Frozen air is a great insulator
- Poor vacuum at room temperature can lead to poor electrical contact at cold temperatures



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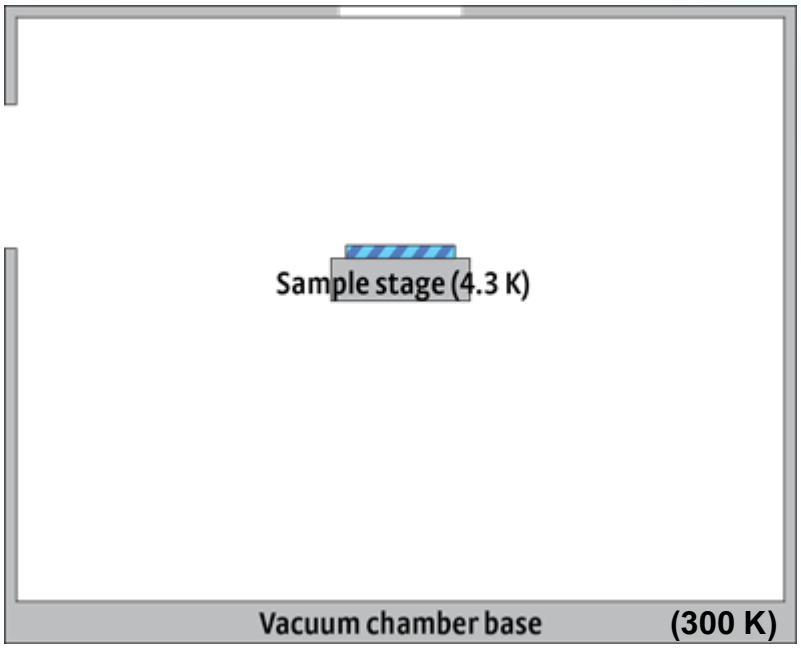
Anatomy of a cryogenic probe station

Thermal radiation

$$\dot{Q} \propto {T_{hot}}^4 - {T_{cold}}^4$$



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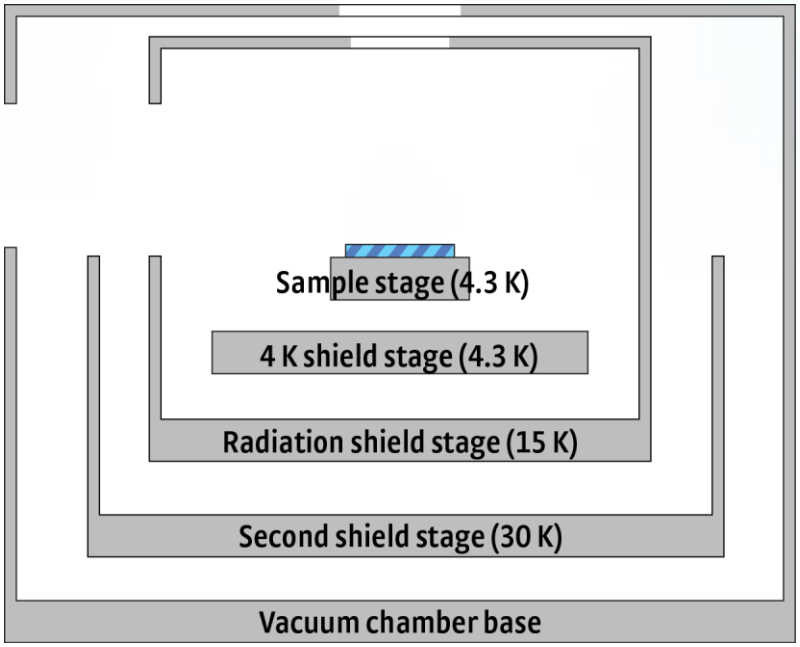
Anatomy of a cryogenic probe station

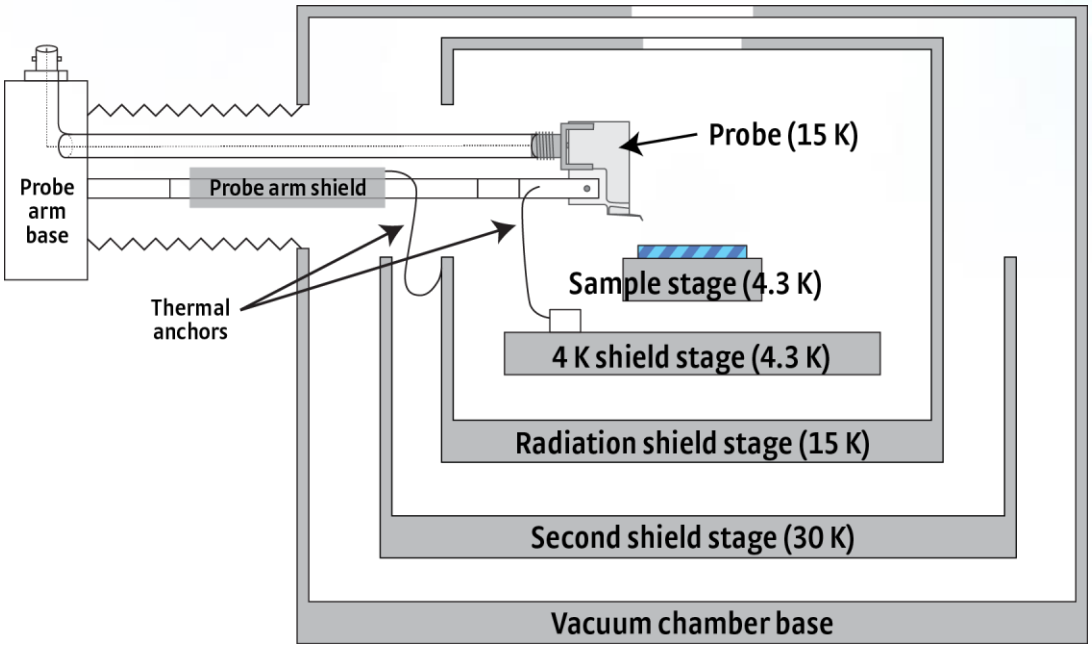
Radiation shield



Lake Shore CRYOTRONICS

Anatomy of a cryogenic probe station

Probe arm



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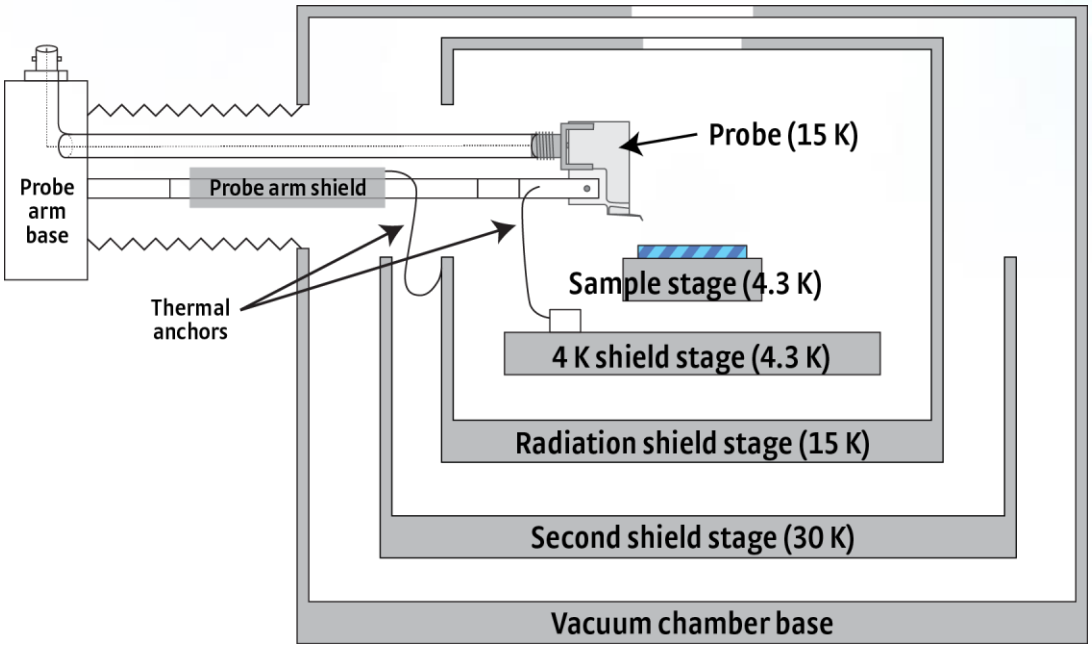
Anatomy of a cryogenic probe station

Probe arm design to limit thermal conduction



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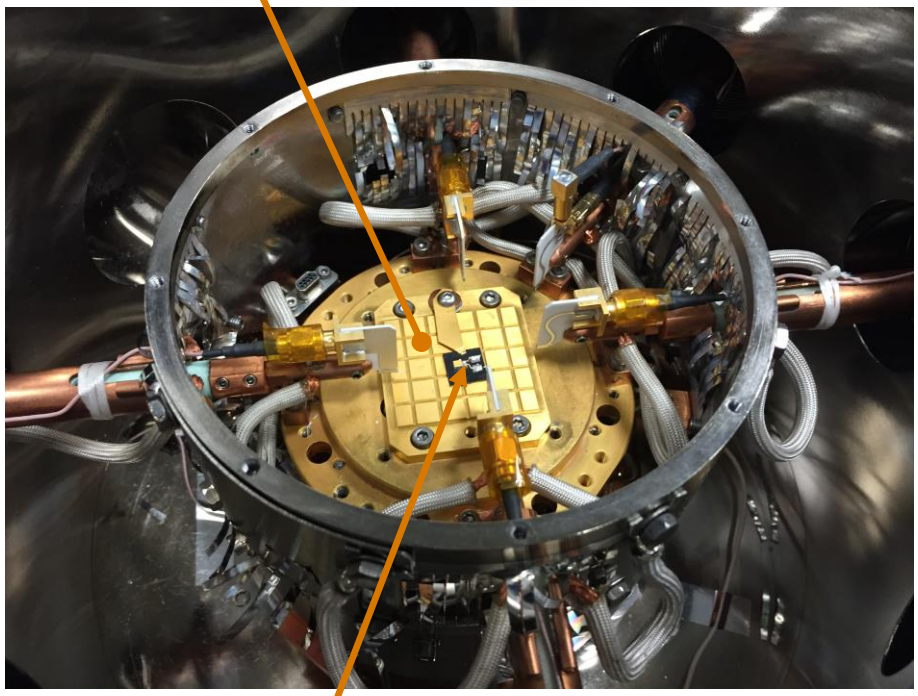
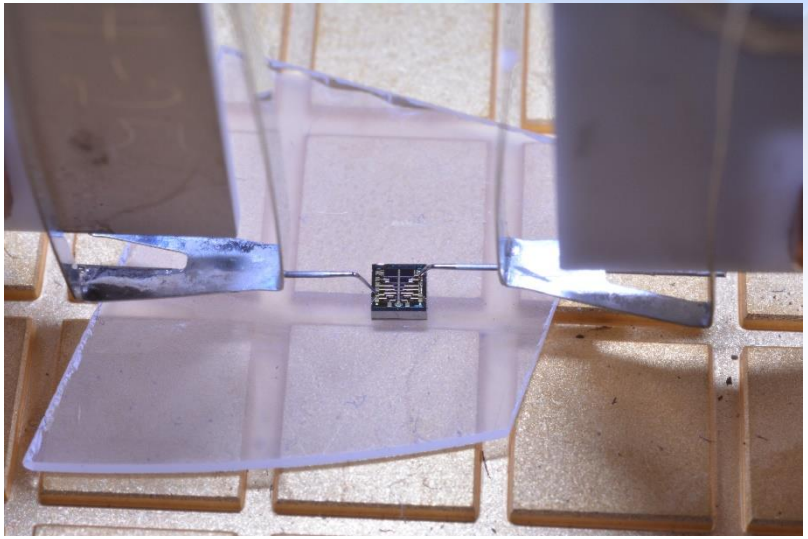
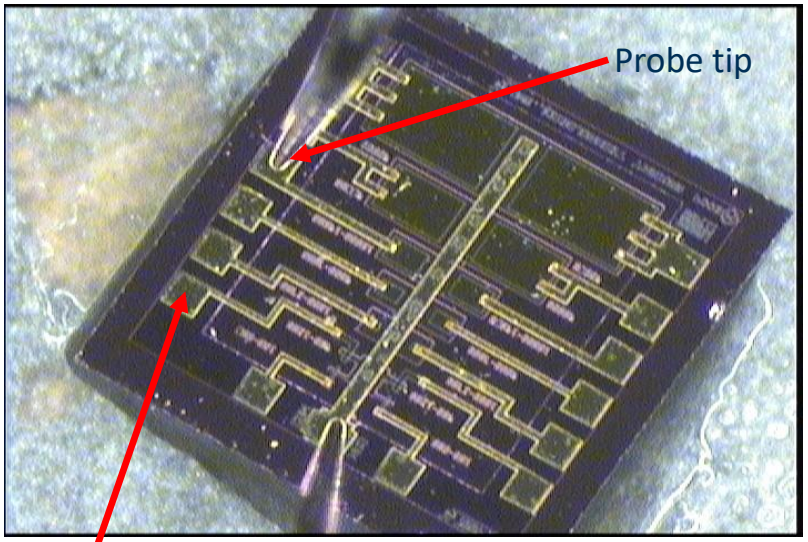
Cryogenic probe stations in a nutshell

The stage gets really cold, or fairly hot
1.3 K to 675 K (-457 °F to 750 °F)



Need to make electrical contacts to a device on the stage





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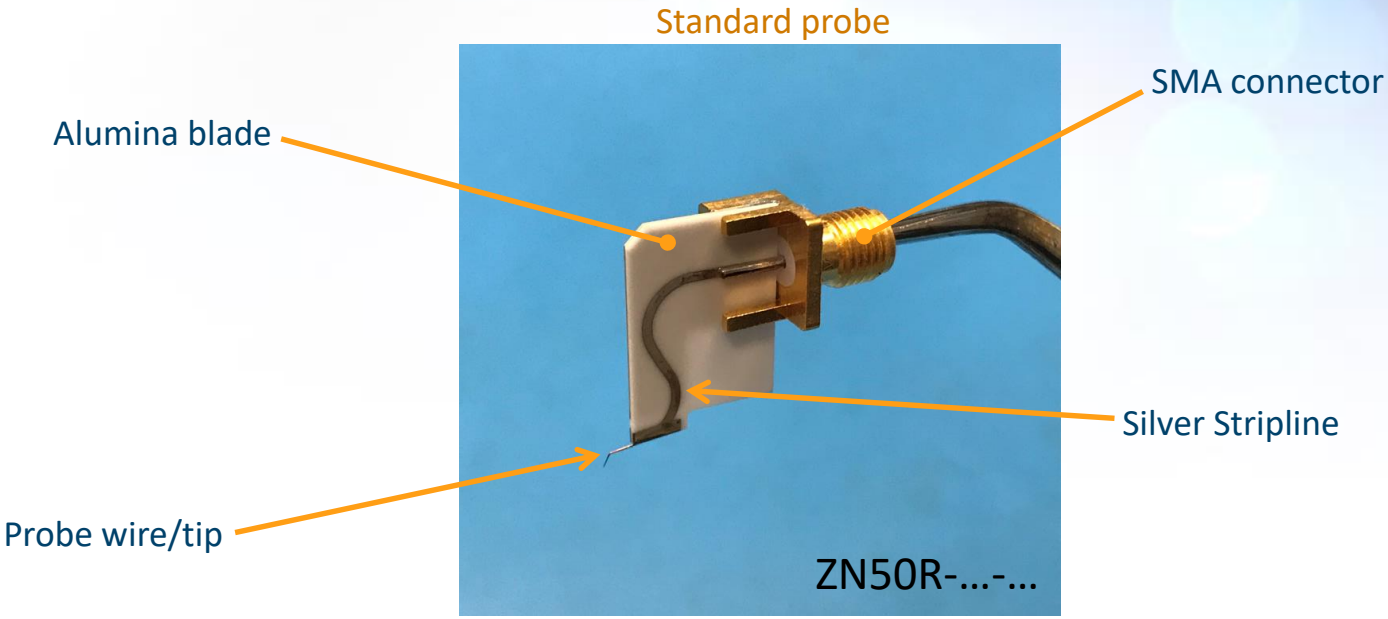
The ZN50 probe

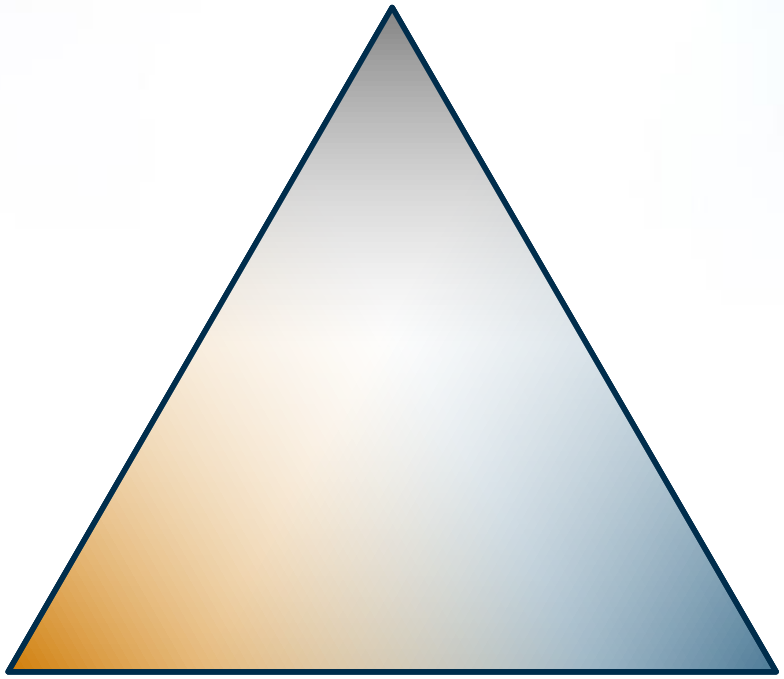


Lake Shore CRYOTRONICS

Tailoring the probe to the application

Probe style

(how are you taking the measurement?)



Wire material

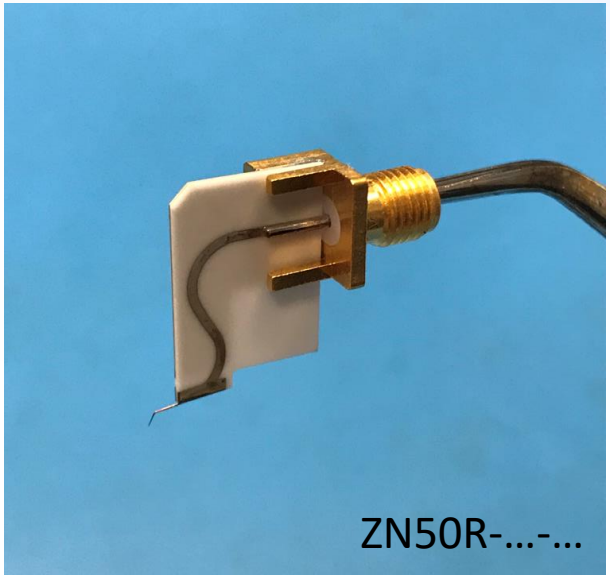
(What are you landing the probes on?)

Tip size

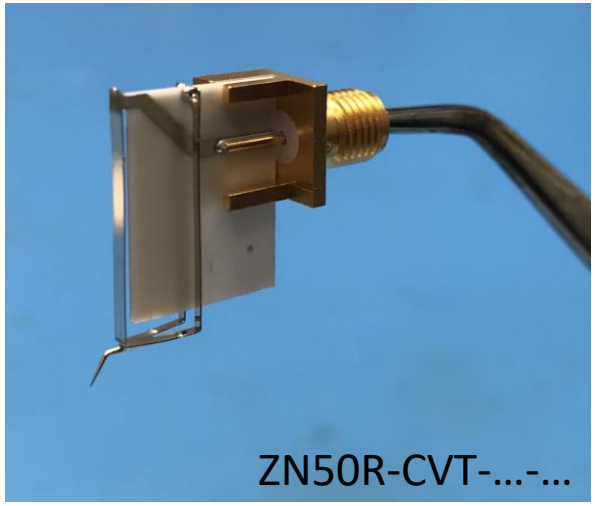
(how big is the probe pad?)

Probe style

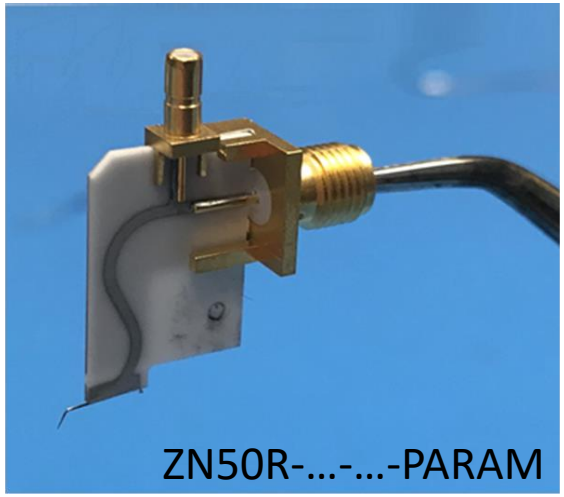
Standard probe



Continuous variable temperature probe



Parametric (or dual connector) probe

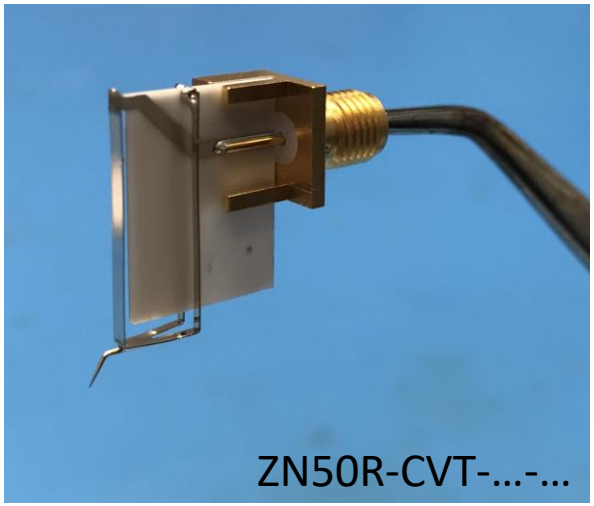


Lake Shore CRYOTRONICS

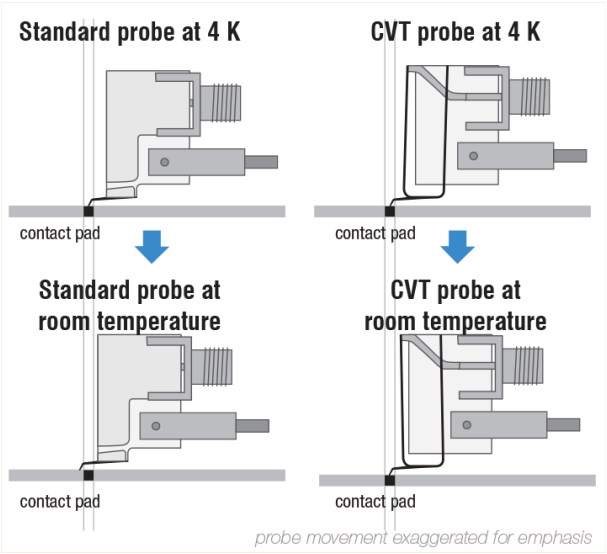
Probe style: CVT

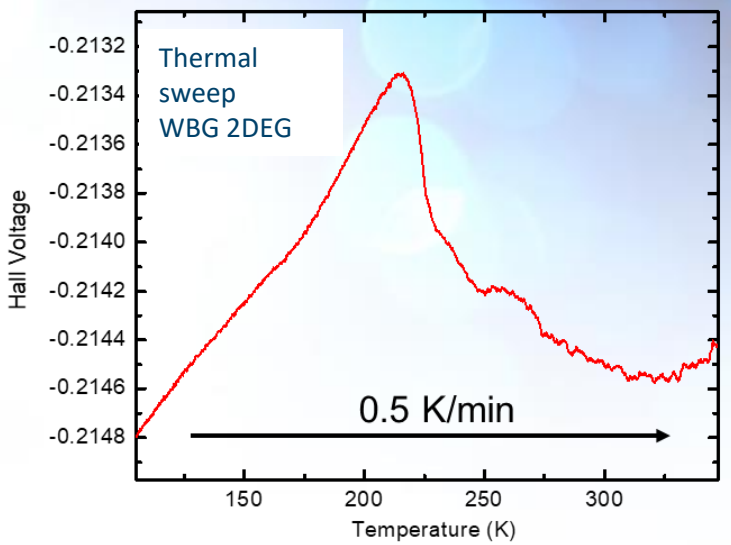
Continuous electrical contact across temperature

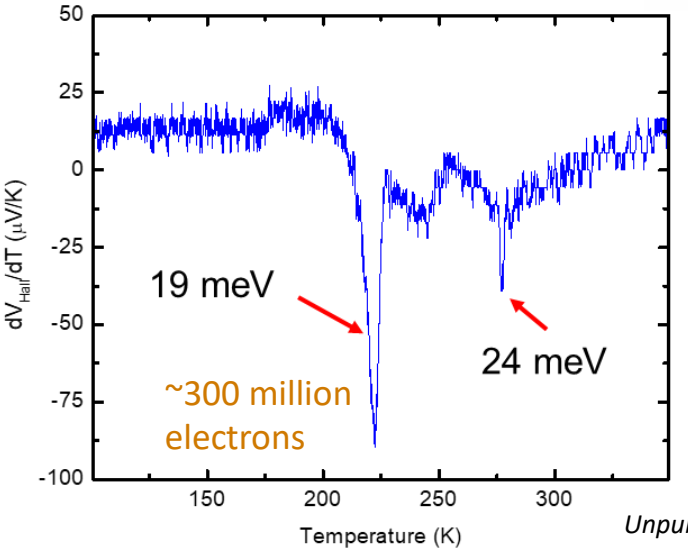
Continuous Variable Temperature Probe



Lake Shore probe station catalog, www.lakeshore.com



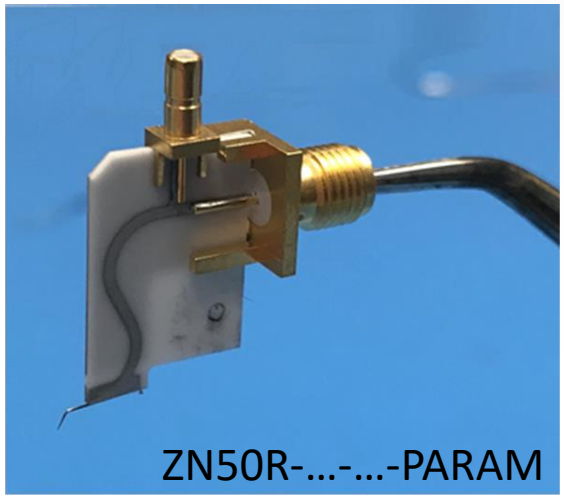




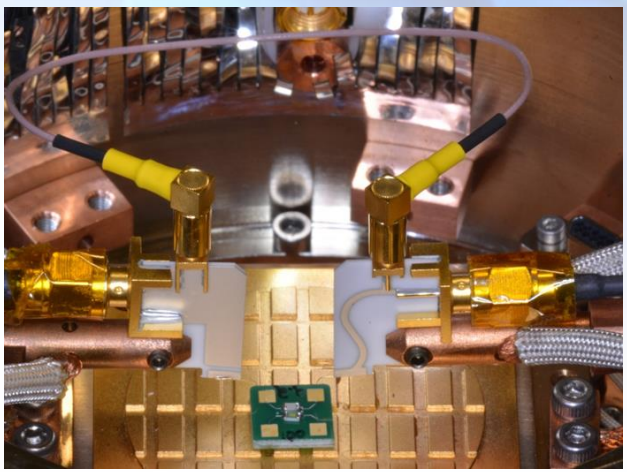
Unpublished

Probe style: parametric (C-V measurements)

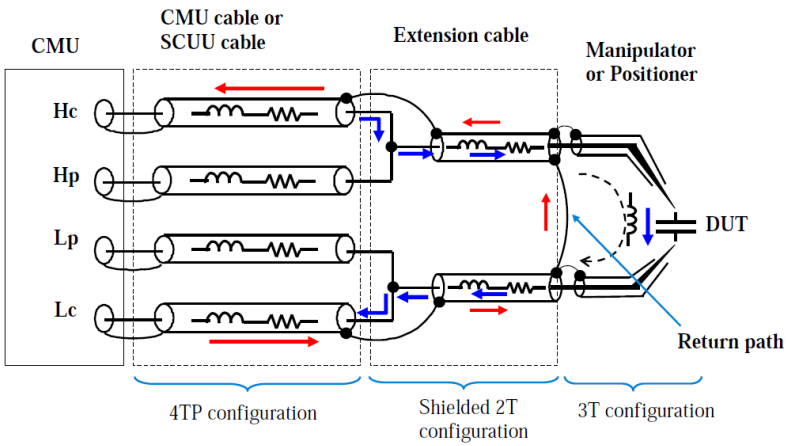
Parametric (or dual connector) probe

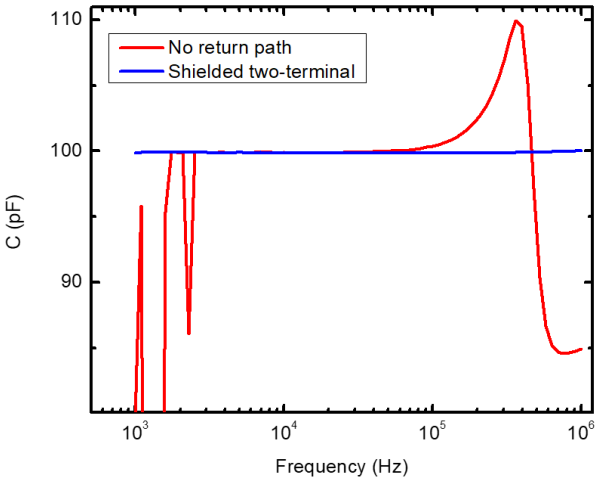


Ground and signal routing in proximity to the DUT



- "S-2T" configuration reduces stray inductance in probe arm cabling – improves reliability of C-V measurement



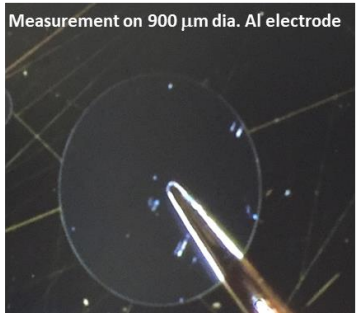


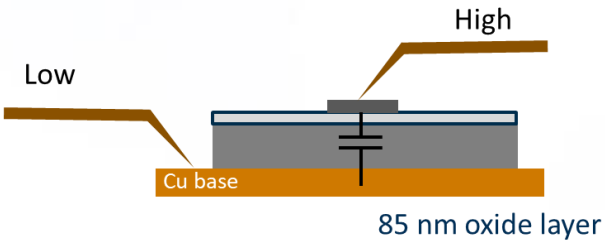
"Variable-Temperature, Wafer-Level Capacitance Measurements" Lake Shore Application Note, www.lakeshore.com

Lake Shore CRYOTRONICS

Temperature-dependent C-V results

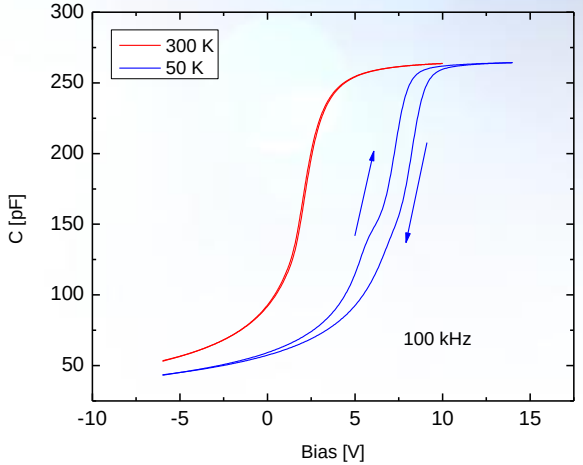
SiC MOS structure



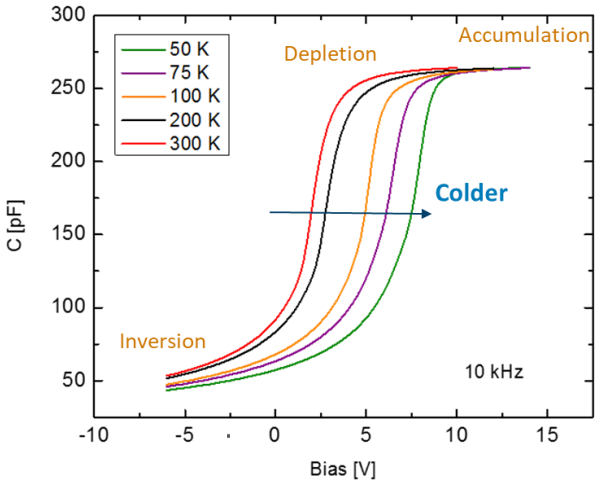


Unpublished

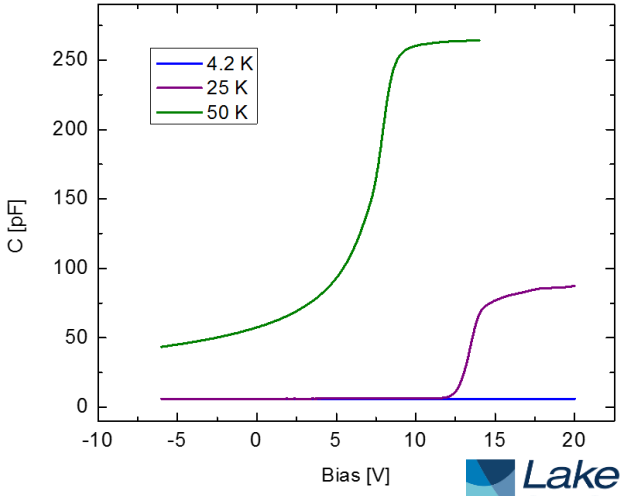
"Clockwise" hysteresis indicative of surface-state traps



Drastic shift in C-V characteristic as temperature is lowered



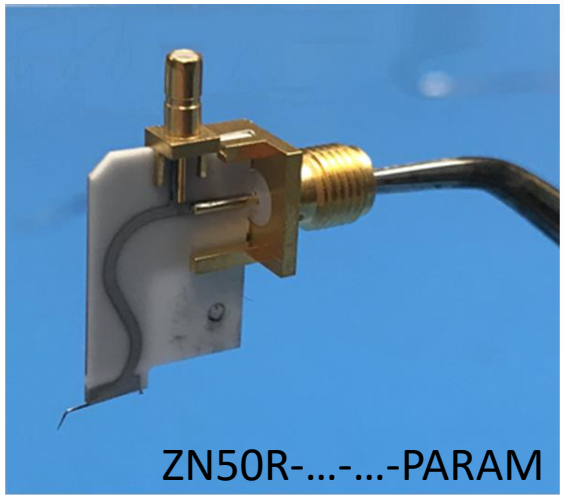
Below 50 K you start seeing carrier freeze out effects



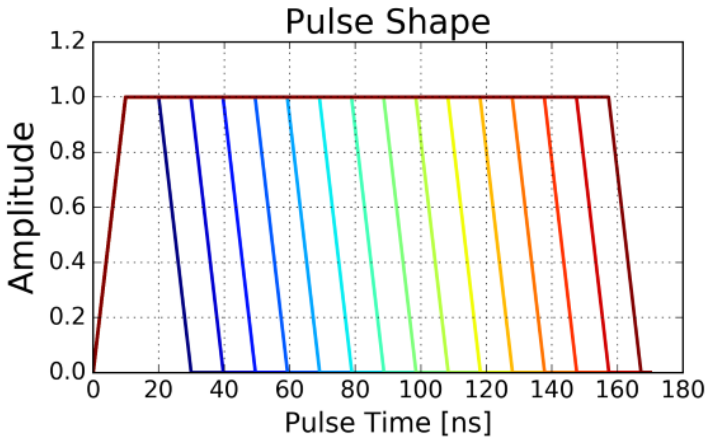
Lake Shore CRYOTRONICS

Probe style: parametric (pulsed measurements)

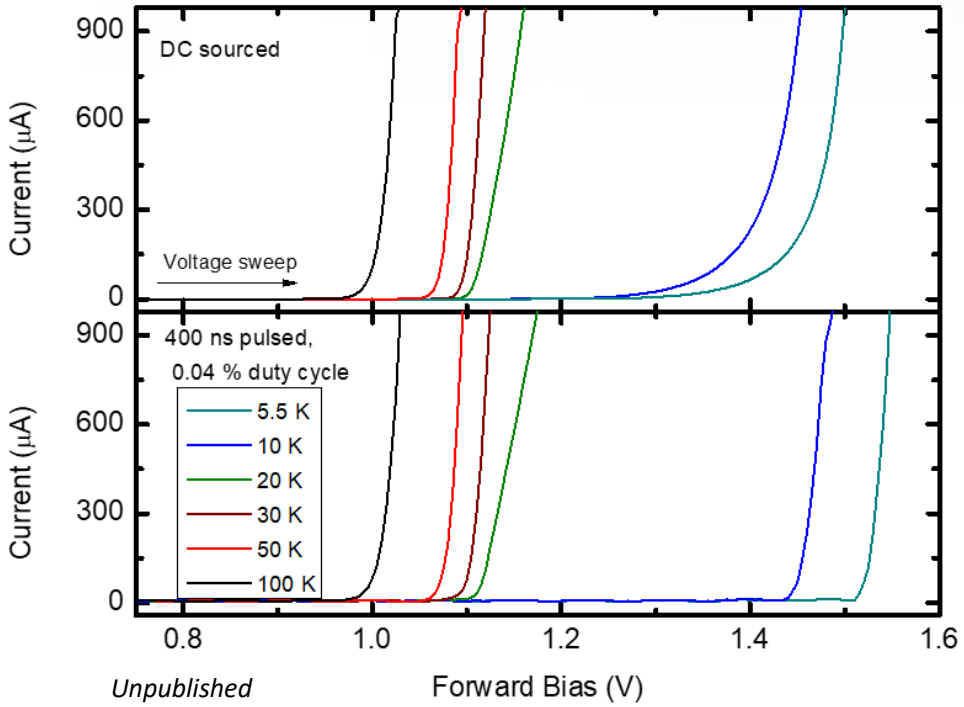
Parametric (or dual connector) probe



Ground and signal routing in proximity to the DUT



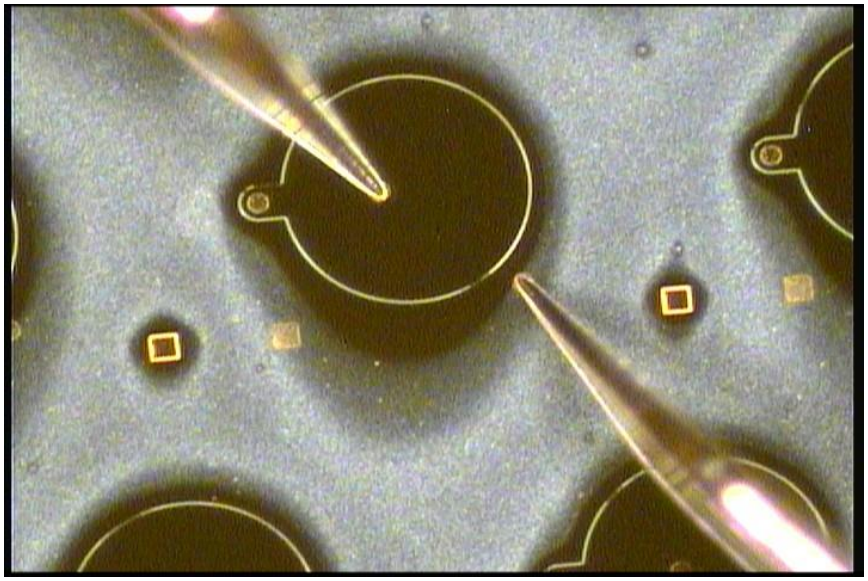
Cryo temperatures: Duty cycle and pulse duration

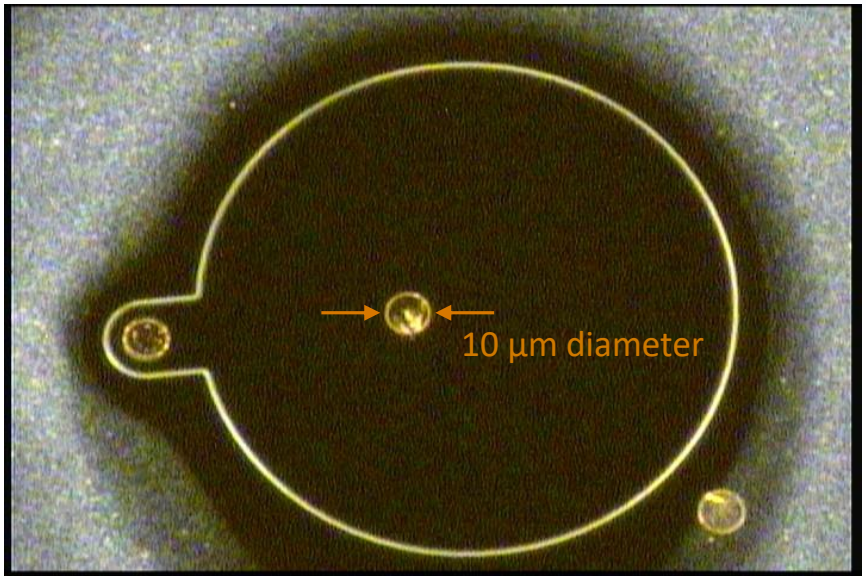


Lake Shore CRYOTRONICS

Probe size

- Largely, probe wire is 250 micron in diameter and is tapered to a point
- Tip size is tailored to the pad size
- Probe point can be as large as 100 µm radius and as small as 3 µm radius



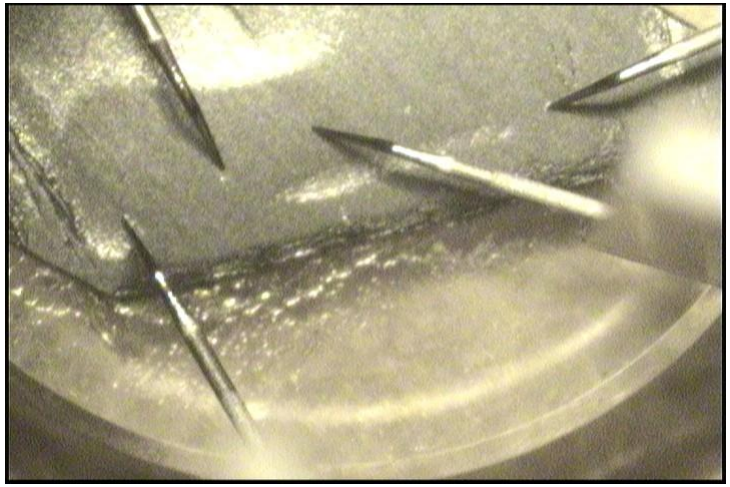


Lake Shore CRYOTRONICS

Probe material

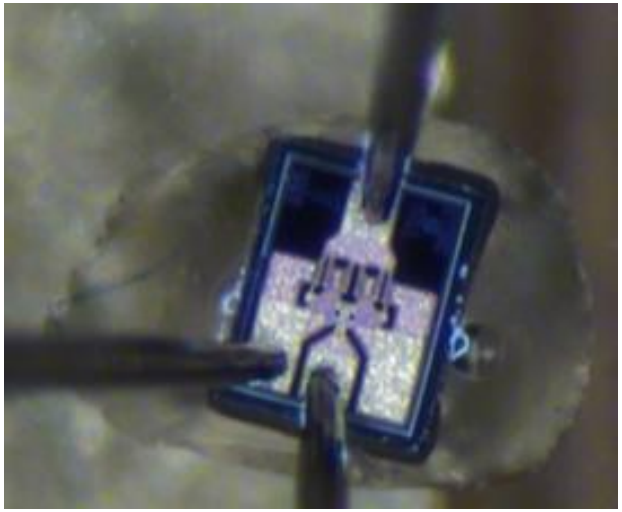
Material	Pro(s)	Con(s)
Beryllium copper (BeCu)	Low contact resistance, easy to clean	Quickly oxides, wire easily deforms
Tungsten (W)	Punctures oxides, robust	Difficult to clean, punctures wrong oxide
Paliney 7 (P7)	High corrosion resistance	Wire easily deforms
Gold-coated tungsten (Au)	Robust + low contact resistance to Au	Au layer wears

Tungsten tips on niobium sheet



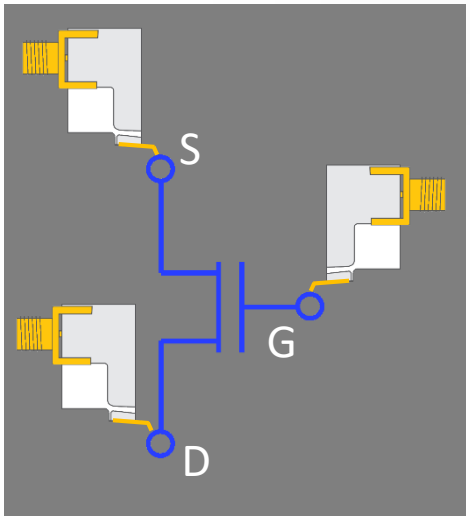
Moh hardness of Nb oxides similar to quartz (~7)

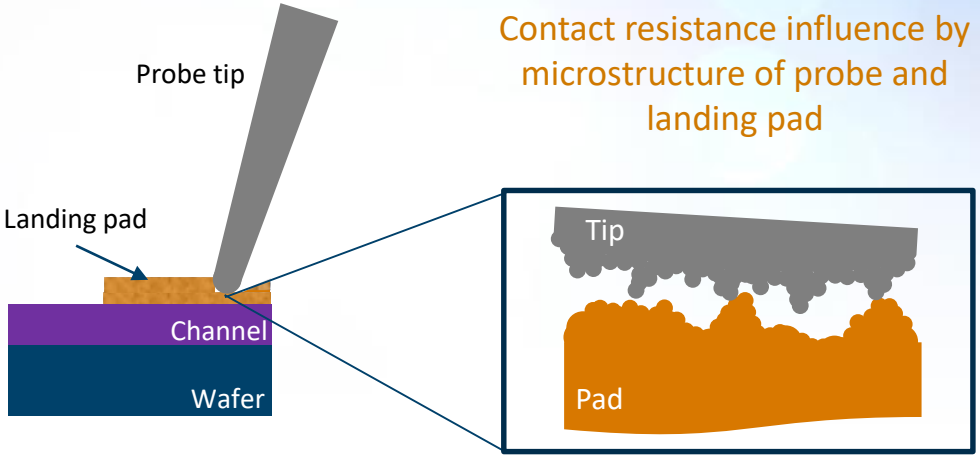
BeCu tips on gold transistor contacts



Moh hardness of Au around 2.5 to 3

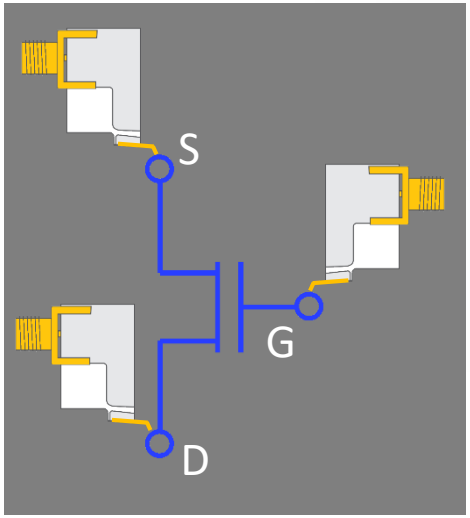
Contact resistance

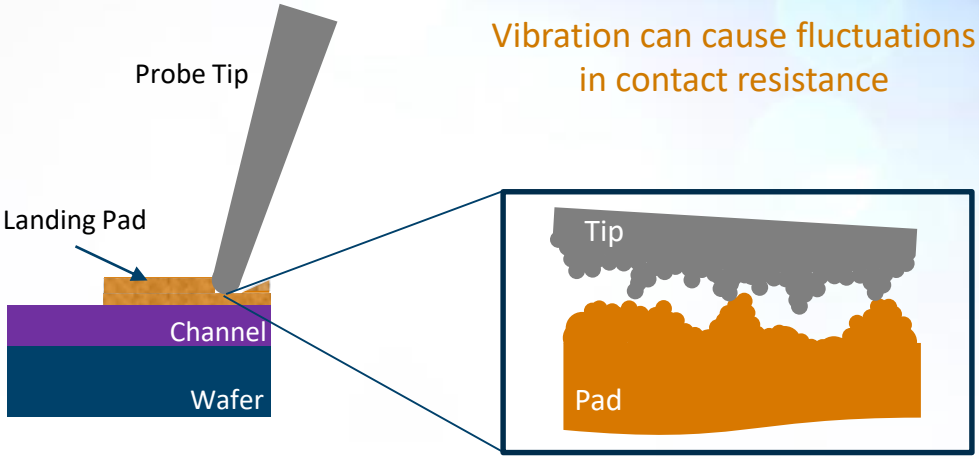




Contact resistance influence by microstructure of probe and landing pad

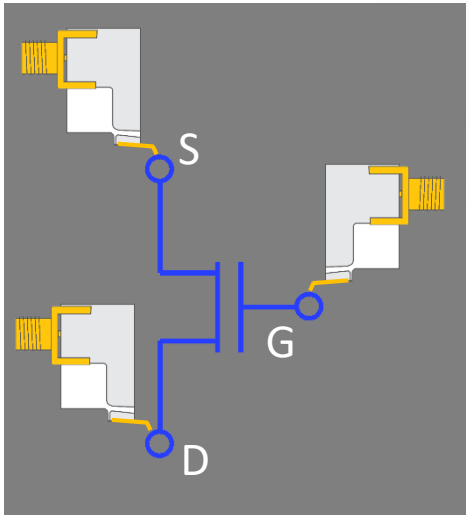
Contact resistance

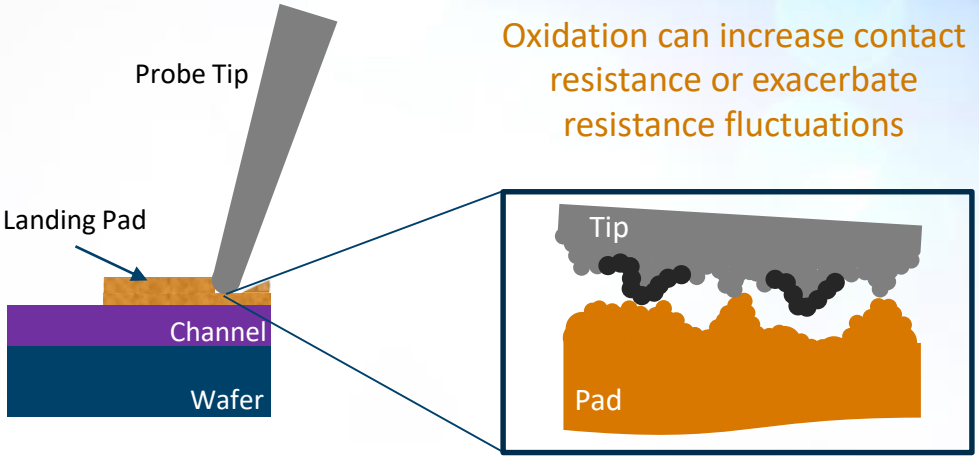




Vibration can cause fluctuations in contact resistance

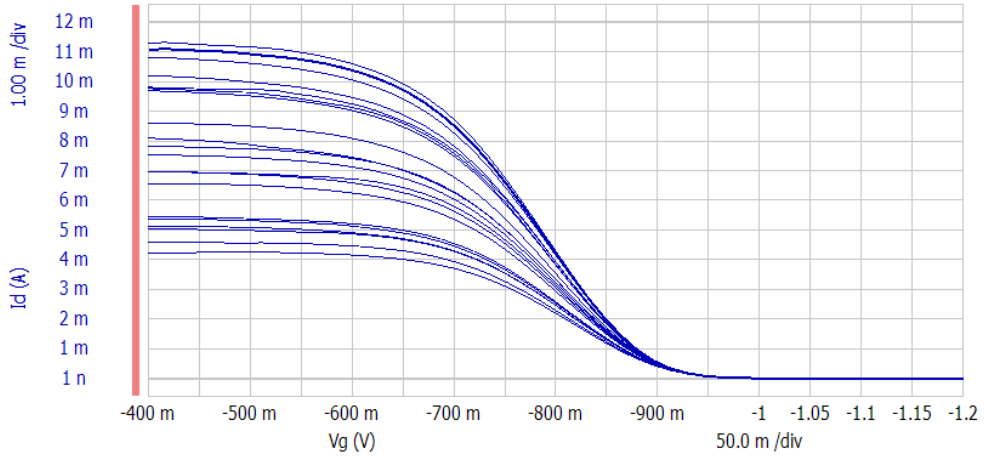
Contact resistance





Oxidation can increase contact resistance or exacerbate resistance fluctuations

Repeated Transfer curves at 77 K

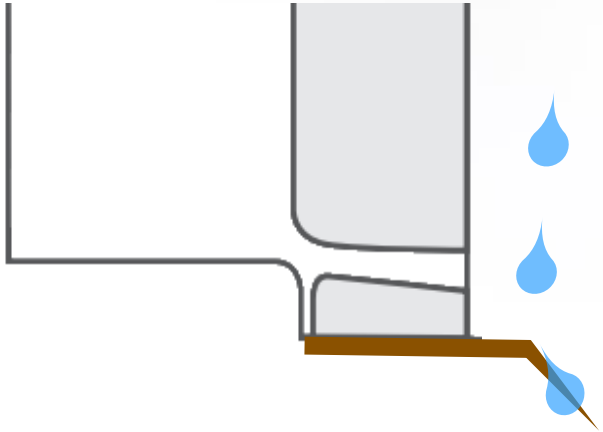


Consistency and repeatability checks are a valuable tool to evaluate contact resistance.

Lake Shore CRYOTRONICS

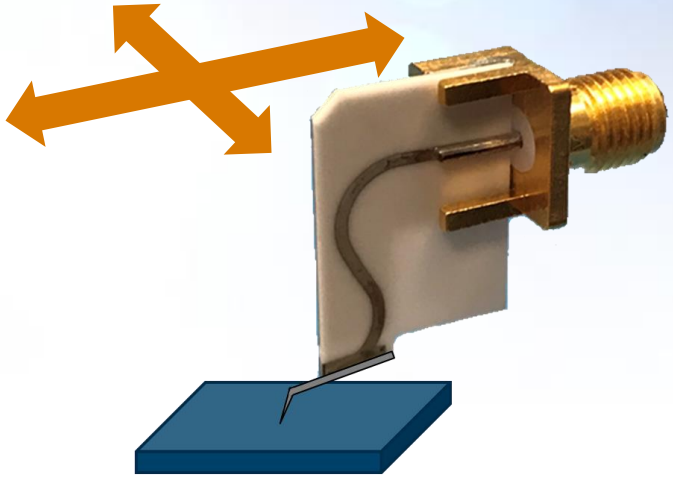
Cleaning dirty probes

BeCu/Au/P7 probe wire



- Organic contaminants removed with solvent
- BeCu oxidation removed with Tarnix, rinse after (see manual)
- Especially for smaller radius tips, apply liquid to knee of probe and let droplets run down probe wire

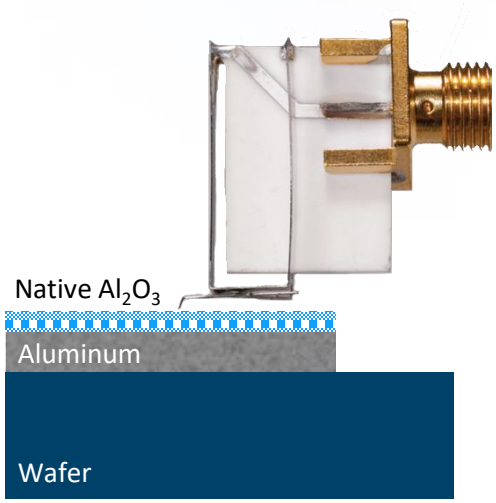
W probe wire



- Organic contaminants removed with solvent
- Don’t recommend corrosives to remove oxidation
- Mechanical removal
  - Tip paper
  - Clean, broken probe blade
  - In a pinch, clean paper with tight grain (Post-Its, surprisingly)

Probe tip tips

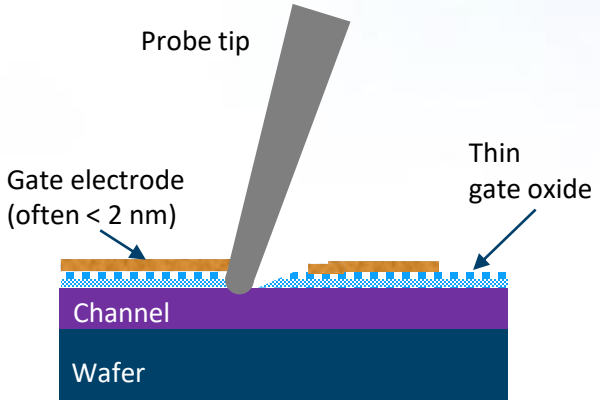
Poor electrical contact with CVT on oxidized probing pads



Consider:

- Standard ZN50 with W probes
- Lateral (left-right) scrubbing of probe pad with CVT probe tip

Probe puncture – electrically shorting gate electrode to channel

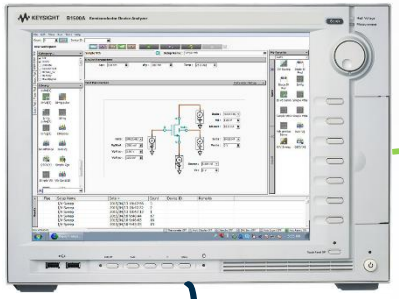


Consider:

- CVT probes with Au-coated tips
- Different probe material (BeCu or P7)
- Reduce overtravel on landing

Lake Shore CRYOTRONICS

The semiconductor analyzer



B1500A/EasyEXPERT
(GPIB interface)

Device measurement

Automated temperature changes

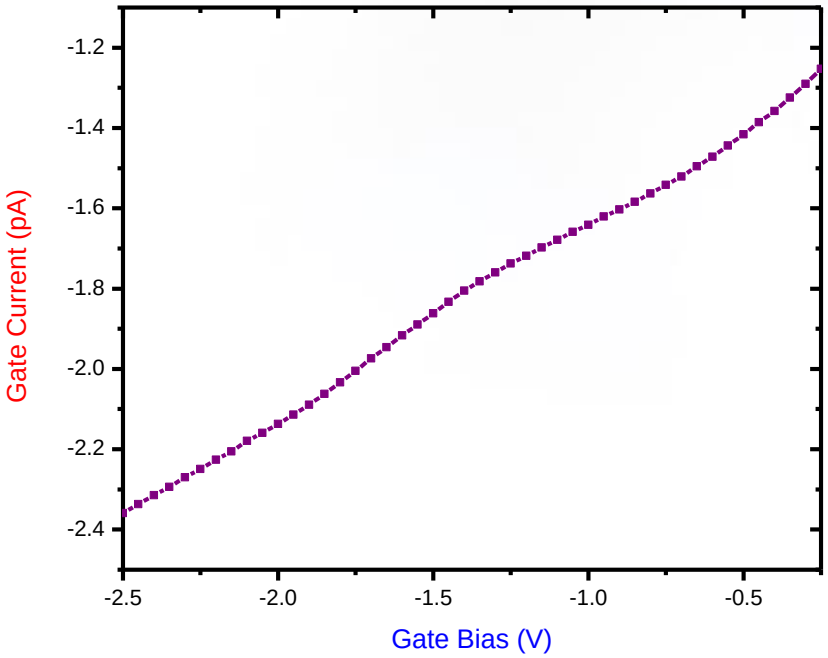
Automated magnetic field changes

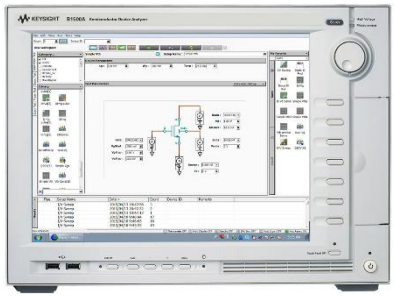
Lake Shore probe station

- Lake Shore temperature and mag field controller interfaces with Keysight B1500
- Lake Shore temperature controller interfaces with Keithley 4200

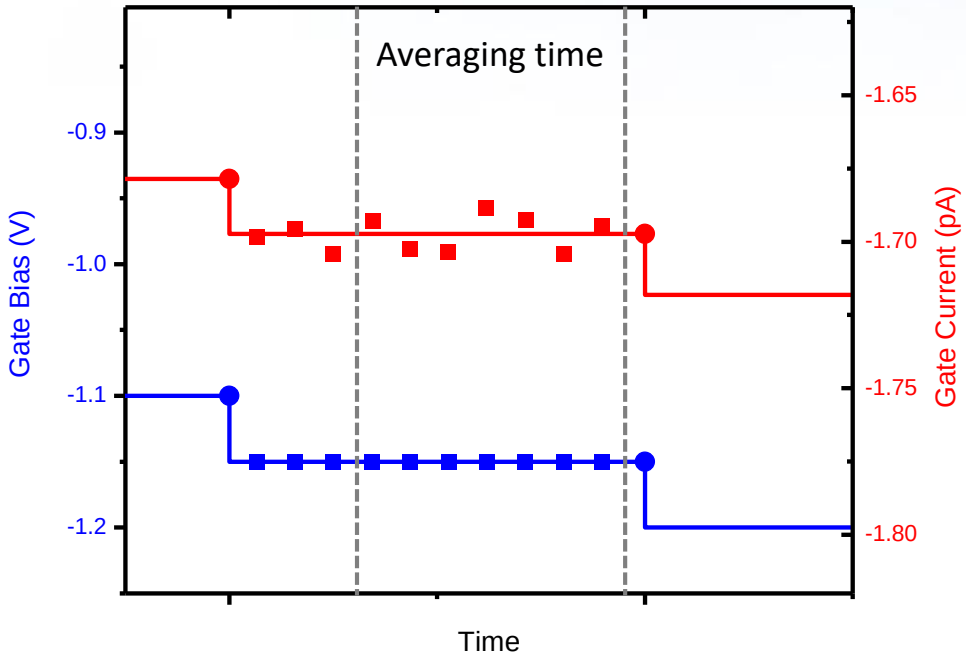
Lake Shore CRYOTRONICS

Low current transport (I-V) measurements





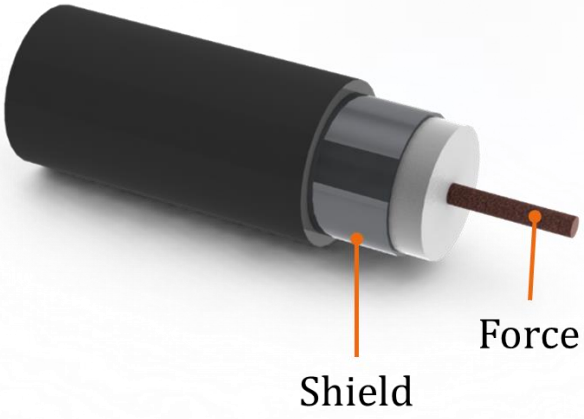
Idealization

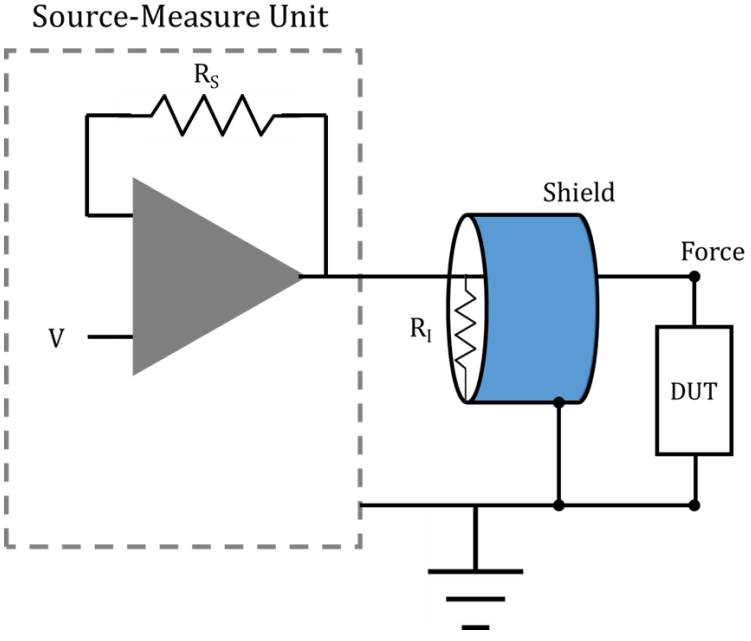


Lake Shore CRYOTRONICS

Low current transport (I-V) measurements

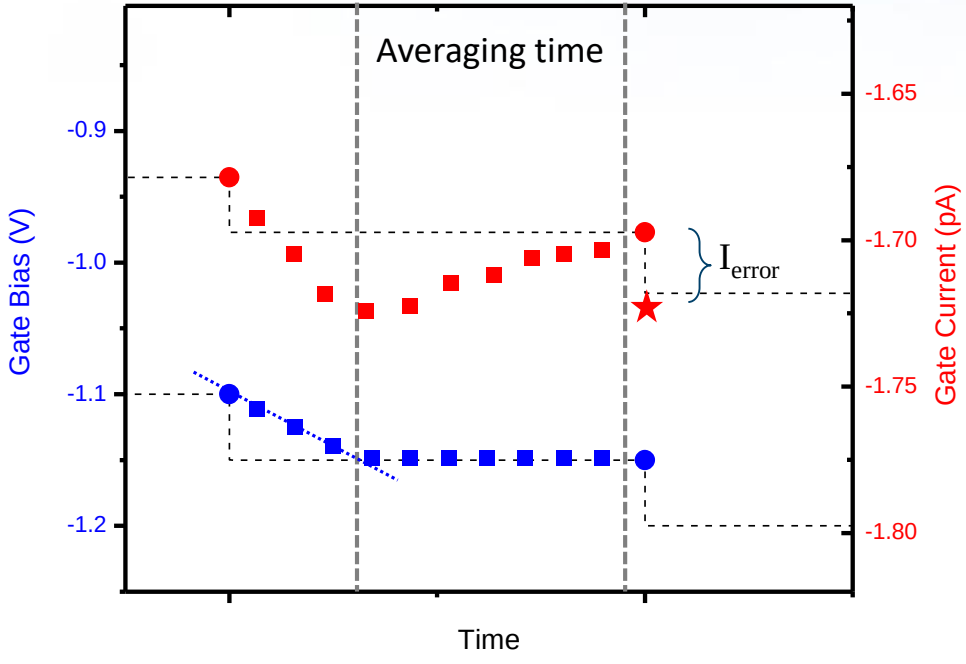
Coaxial





Charging current due to cable capacitance

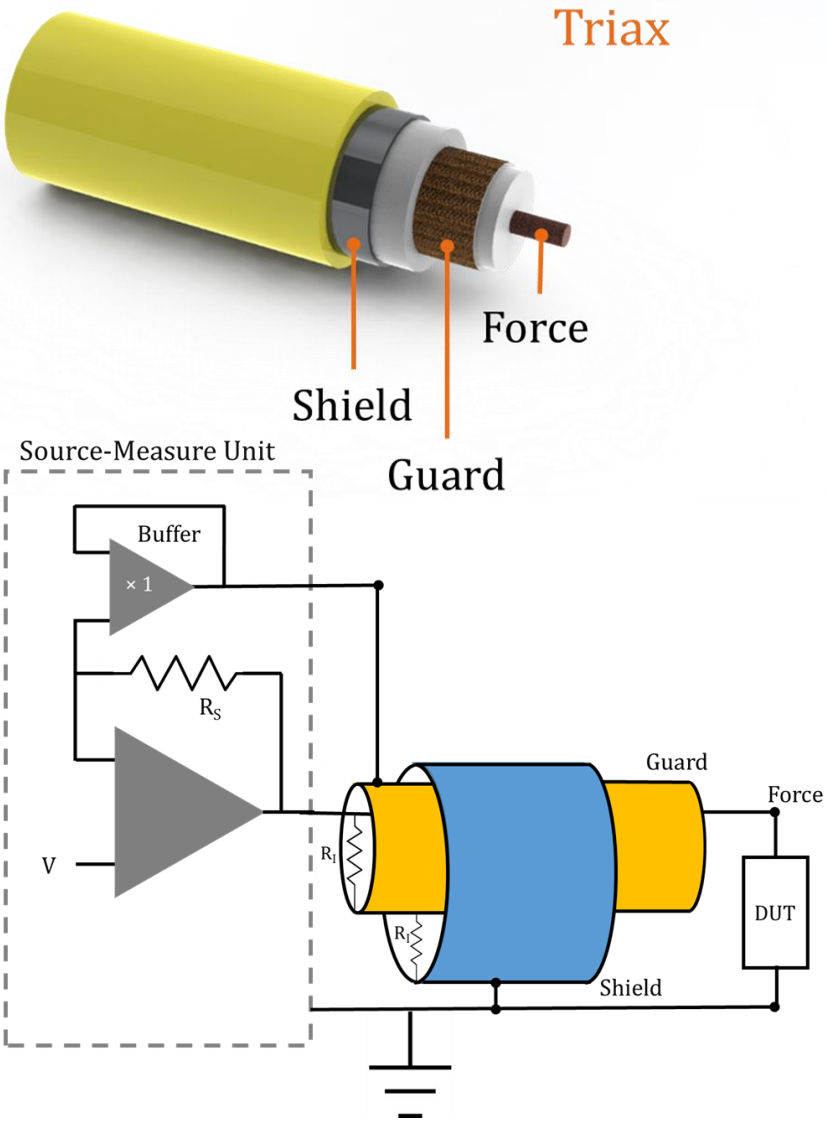
$$I_C = C\frac{dV}{dt}$$



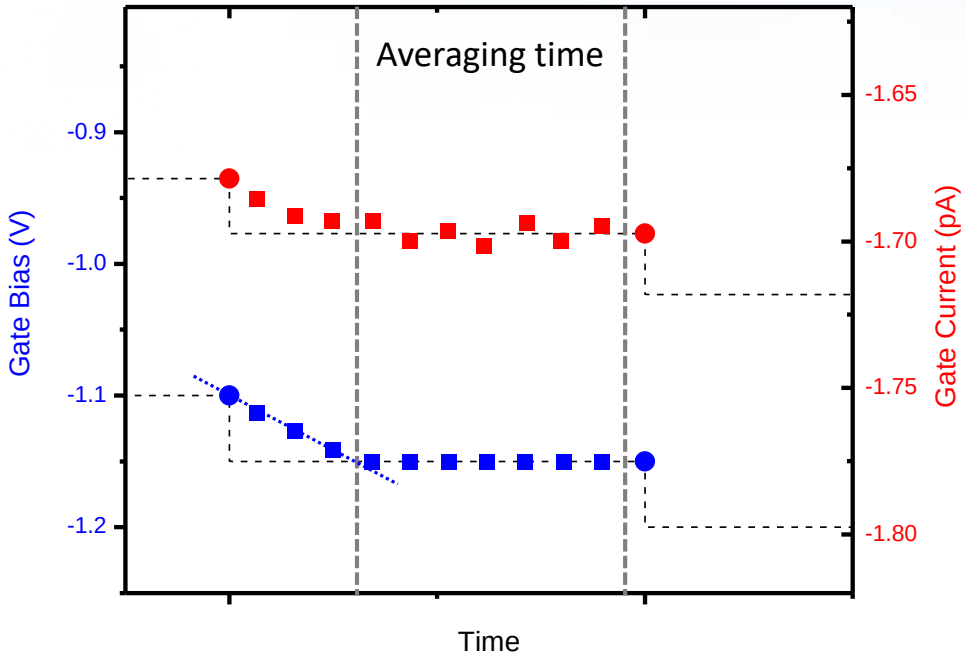
"Considerations for Low Current Measurements in Cryogenic Probe Stations"
Lake Shore Application Note, www.lakeshore.com

Lake Shore CRYOTRONICS

Low current transport (I-V) measurements



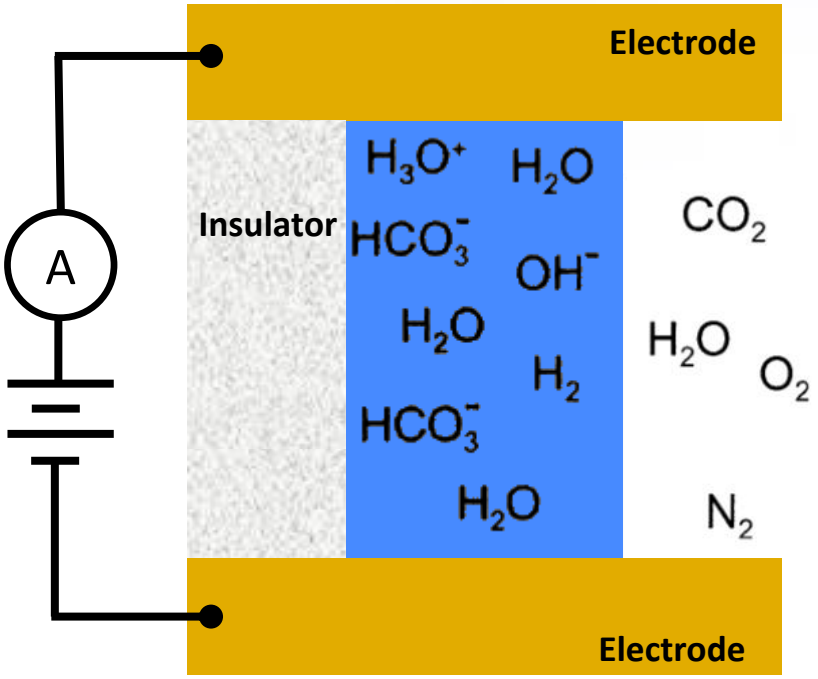
Guard and force at same potential to minimize effect from charging current



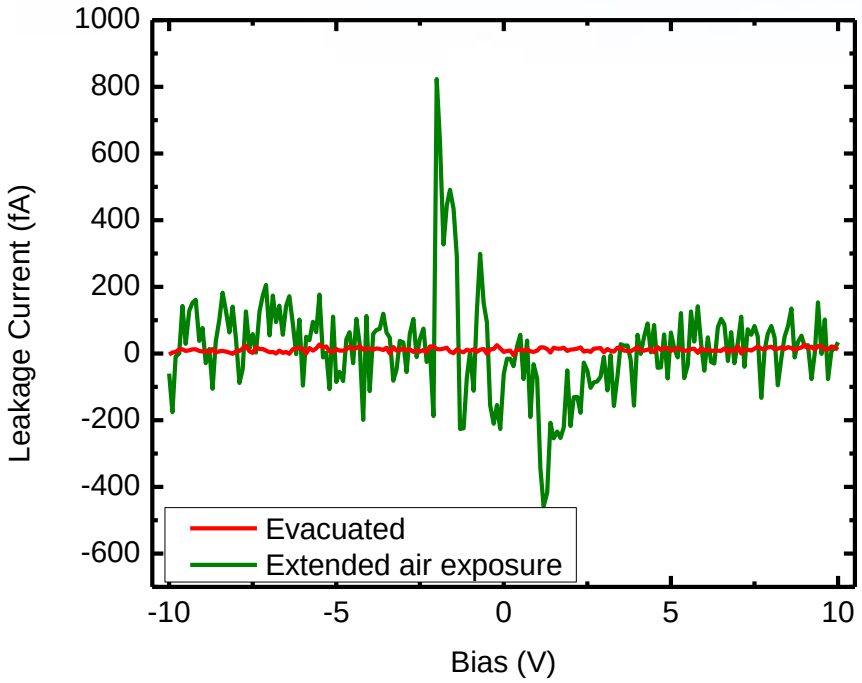
"Considerations for Low Current Measurements in Cryogenic Probe Stations" Lake Shore Application Note, www.lakeshore.com

Lake Shore CRYOTRONICS

Low current transport (I-V) measurements



Water vapor absorbed on surfaces can open additional, unintended conduction channels

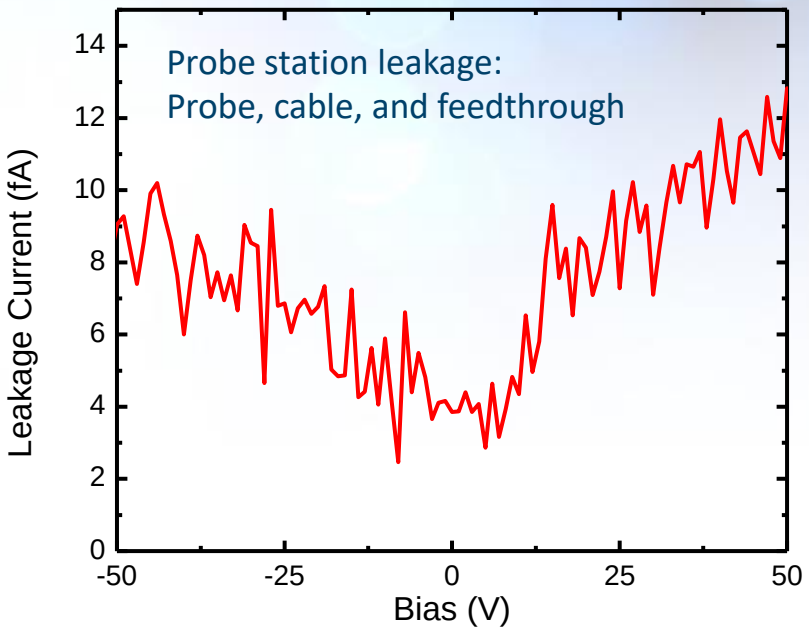


Evacuate or gas purge your probed measurements

Lake Shore CRYOTRONICS

Low current transport (I-V) measurements

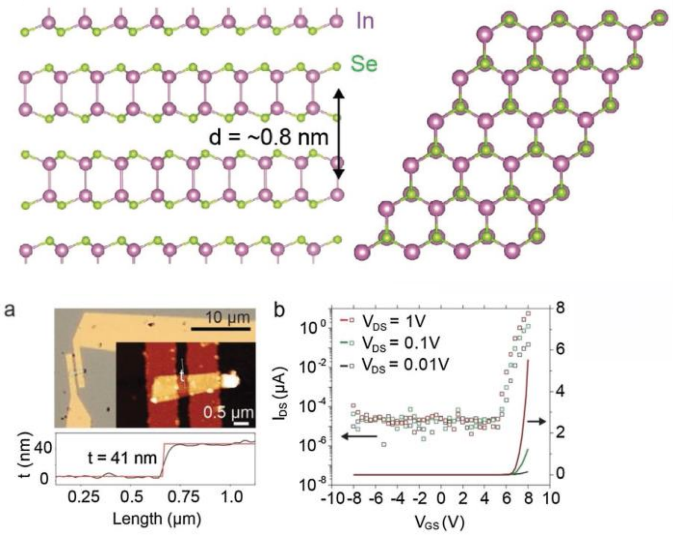
- Triaxial configuration for low-current measurements
  - 3-lug, triaxial vacuum feedthrough
  - Guarded measurement from analyzer to the probe
  - Optional triaxial sample stage for backside device contact
- Use high quality triaxial cabling from instrumentation to prober
- Minimize flexing of cabling



Lake Shore CRYOTRONICS

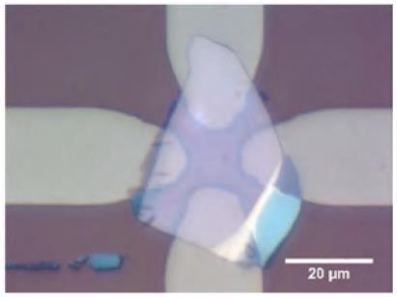
~~Cryogenic~~ Evacuated transport (I-V) measurements

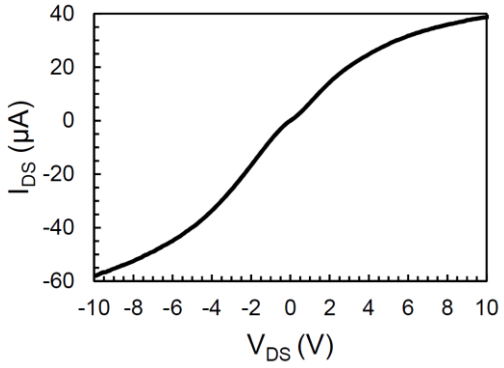
InSe

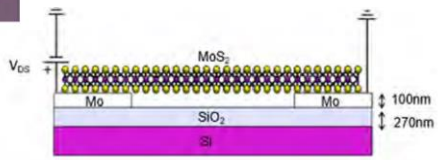


- High vacuum, low-leakage probing ideal for characterization of devices fabricated from air-sensitive 2D materials

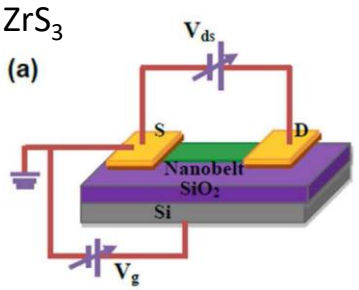
MoS_2

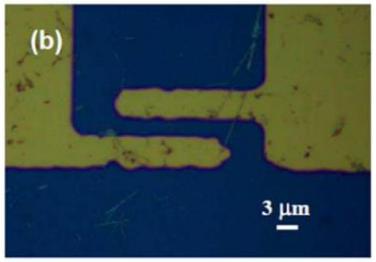


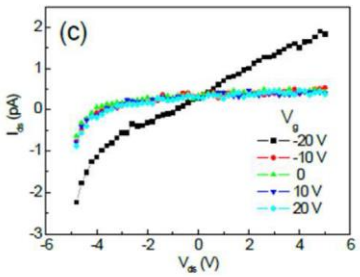


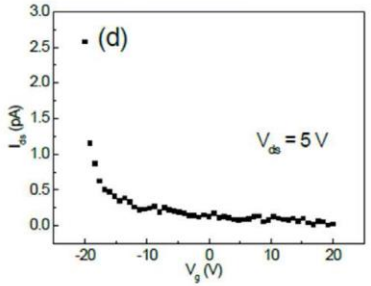


ZrS_3









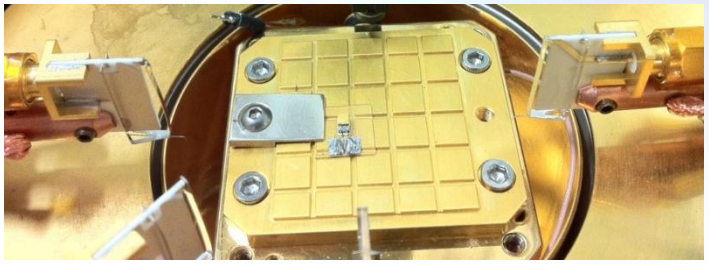
Lake Shore CRYOTRONICS

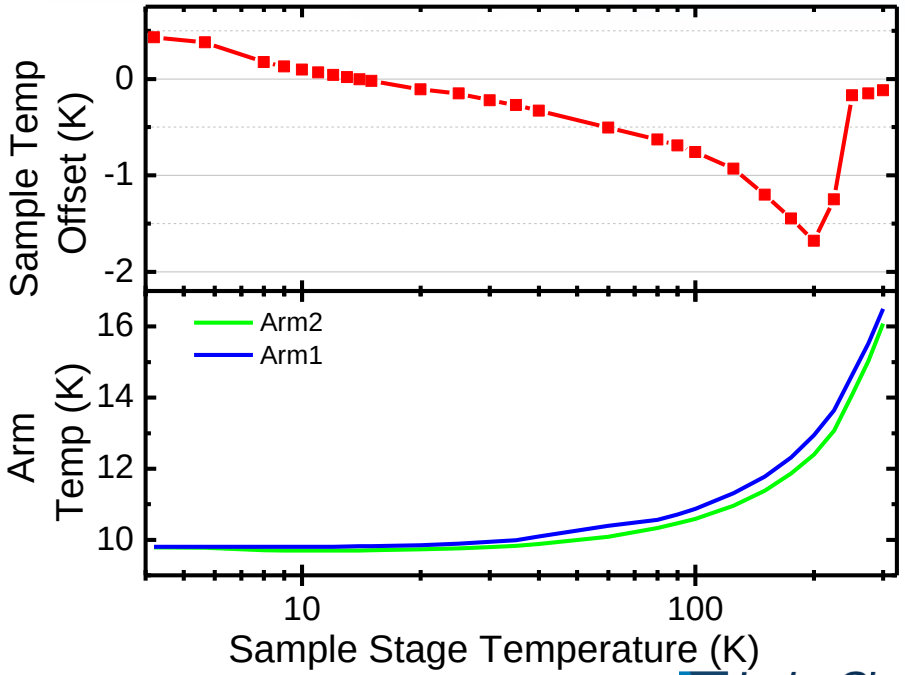
Cryogenic transport (I-V) measurements

Thermal considerations

- Good device contact to thermal sample holder
- Thermally anchored probes
  - Minimizes heat load on device
  - Configurable for various operational conditions

CPX-VF probe station





Forthcoming Lake Shore Application Note

Lake Shore CRYOTRONICS

Cryogenic transport (I-V) measurements

Recommended sample mounting

Method	Pro(s)	Con(s)
GE varnish (IMI 7031)	High thermal conductance	Long cure time, soaking sample and holder in aggressive solvent to remove
Vacuum grease & clamping	Quick sample exchange, good thermal conductance	Probe interference with clamps, wipe clean with Xylene
Silver paint & paste	Backside electrical contact, reasonable thermal conductance	When cleaning, mobile silver particles can short or damage devices
Carbon paste	Backside electrical contact, reasonable thermal conductance, can be used at higher temperatures	When cleaning , mobile carbon particles can short or damage devices
Cyanoacrylate (thin layer)	Quick cure, easy removal, suitable for small surface area	May not endure repeated thermal cycling

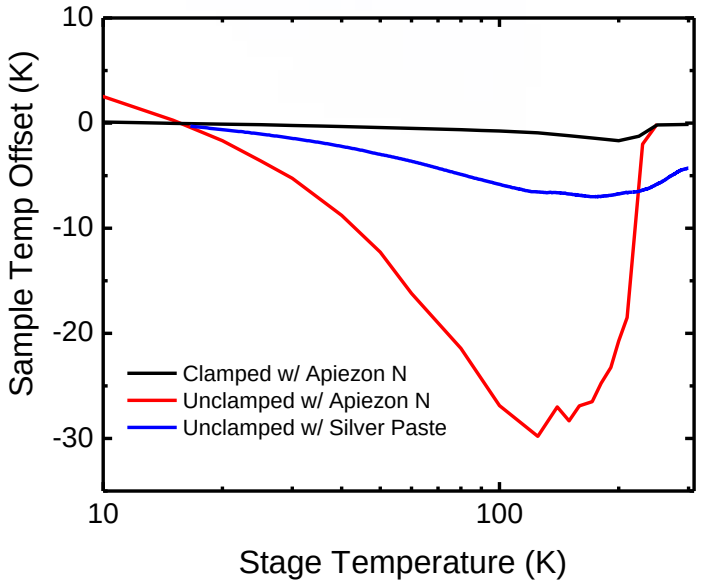
Not recommended for thermal reasons

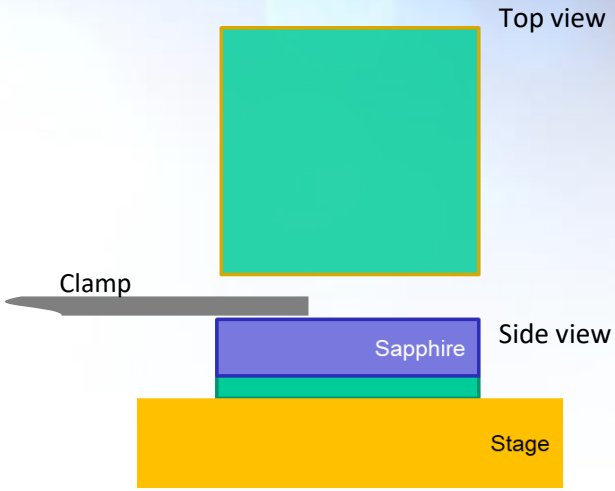
- Double-sided carbon tape
- Kapton tape
- Vacuum grease with no clamping

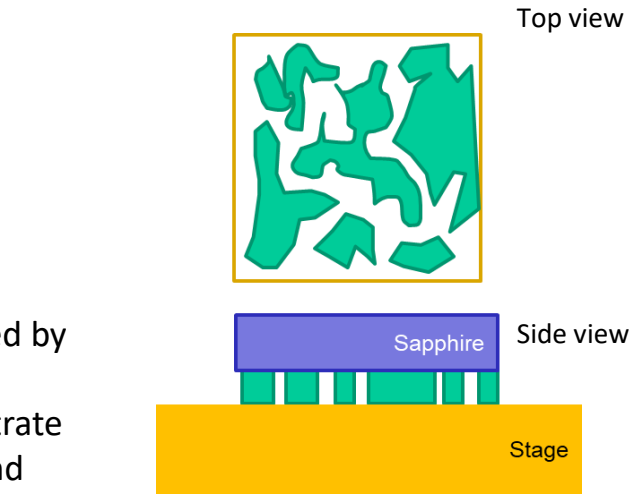
Forthcoming Lake Shore Application Note

Cryogenic transport (I-V) measurements

If good mechanical clamping of substrate to sample stage is not possible, silver paste under sample offers better thermal contact than N-grease alone







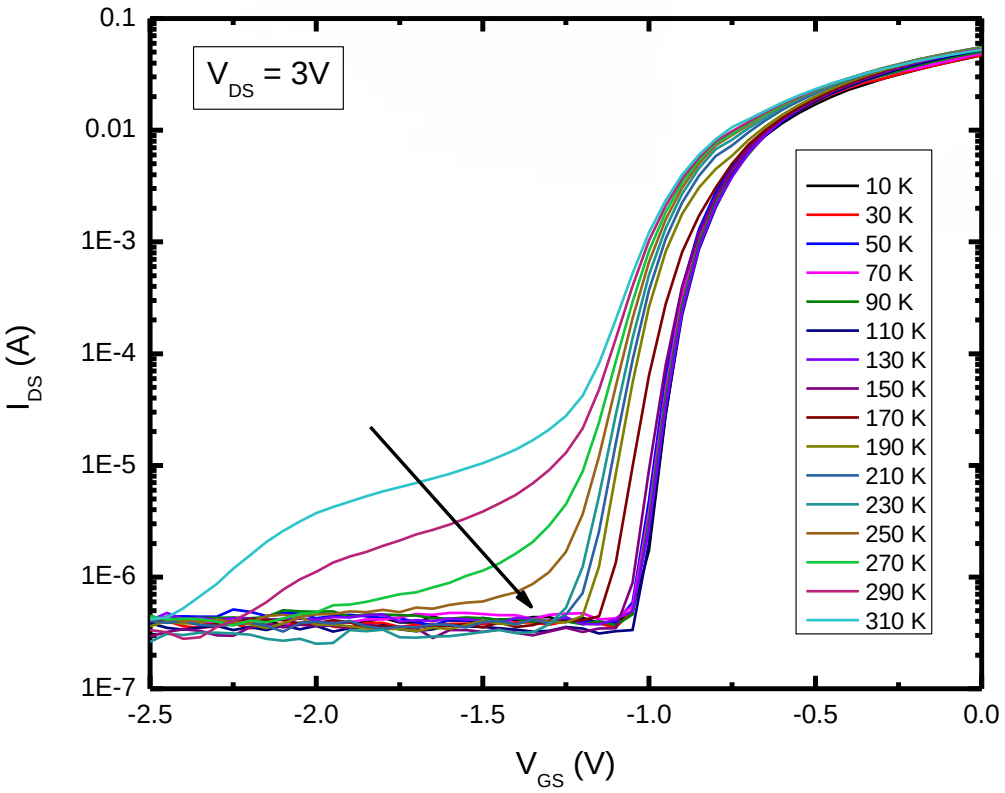
- Low temperature induced strain in polymer network is relieved by coarsening of Apiezon N film
- Coarsening results in spotty thermal transport to device substrate
- Applied clamping force changes thermodynamic landscape and reduces the onset film segmentation

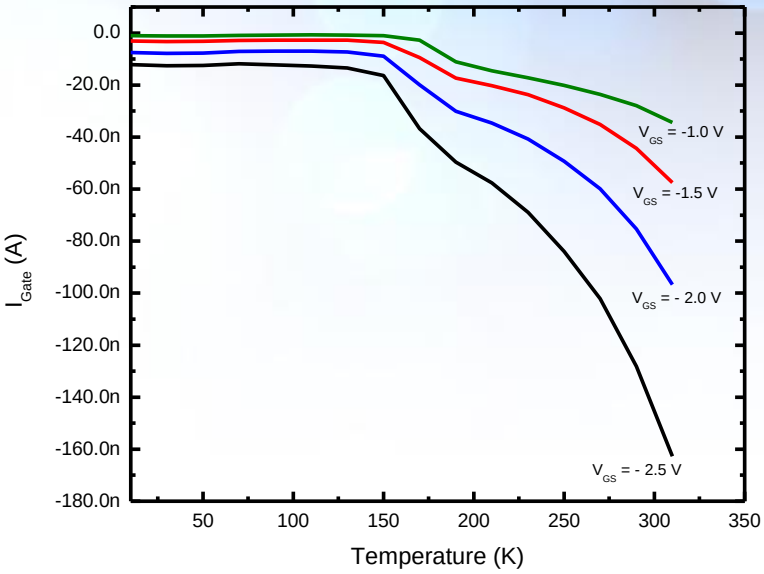
Forthcoming Lake Shore application note

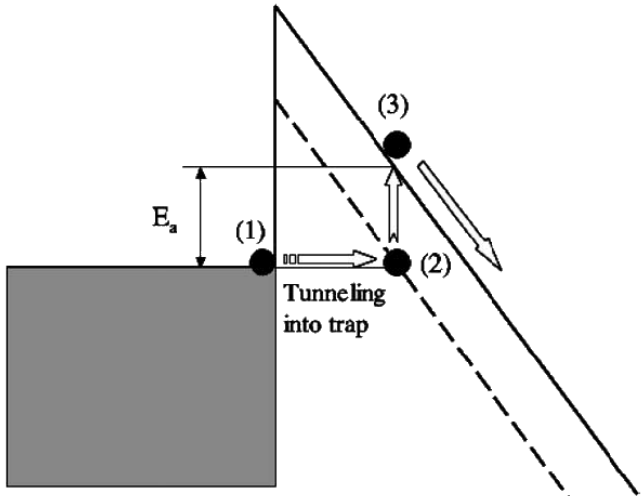
Lake Shore CRYOTRONICS

Variable temperature pHEMT results

Temperature-dependent measurements revealed leakage mechanism





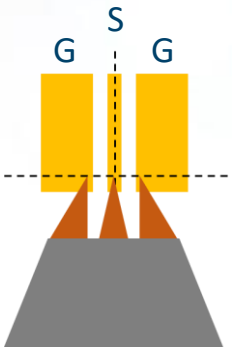


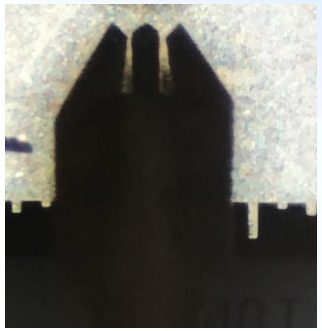
"Exploring Off-state Breakdown of GaAs pHEMTs at Cryogenic Temperatures"
Lake Shore Application Note, www.lakeshore.com

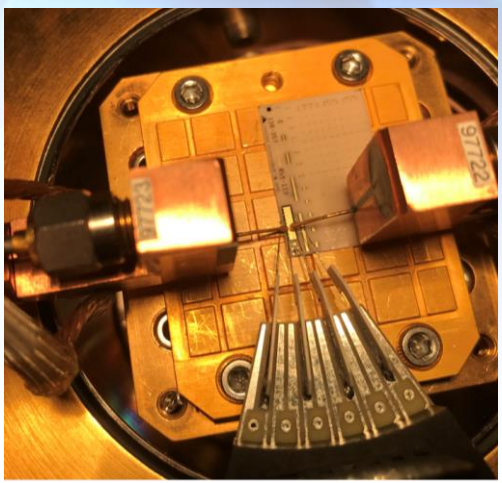
Lake Shore CRYOTRONICS

Microwave probing

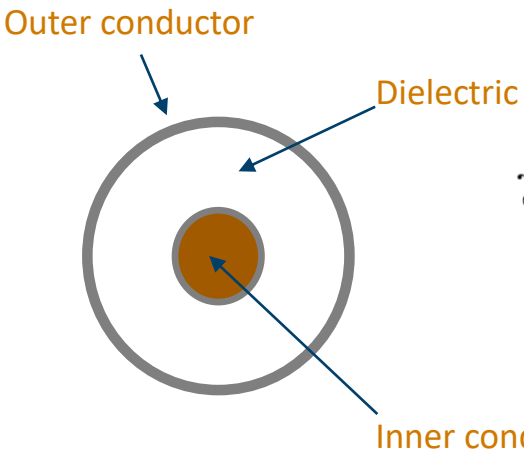
- Cabling and cryogenic probes for:
  - DC to 40 GHz
  - DC to 67 GHz
- Calibration substrates

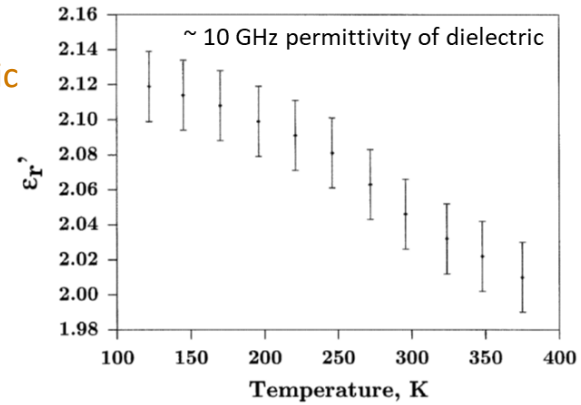




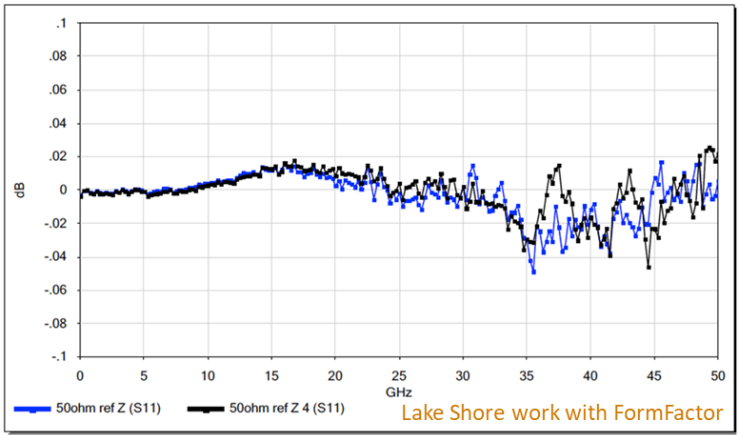


Recommend mounting calibration substrate on sample stage and executing calibration at every temperature of interest





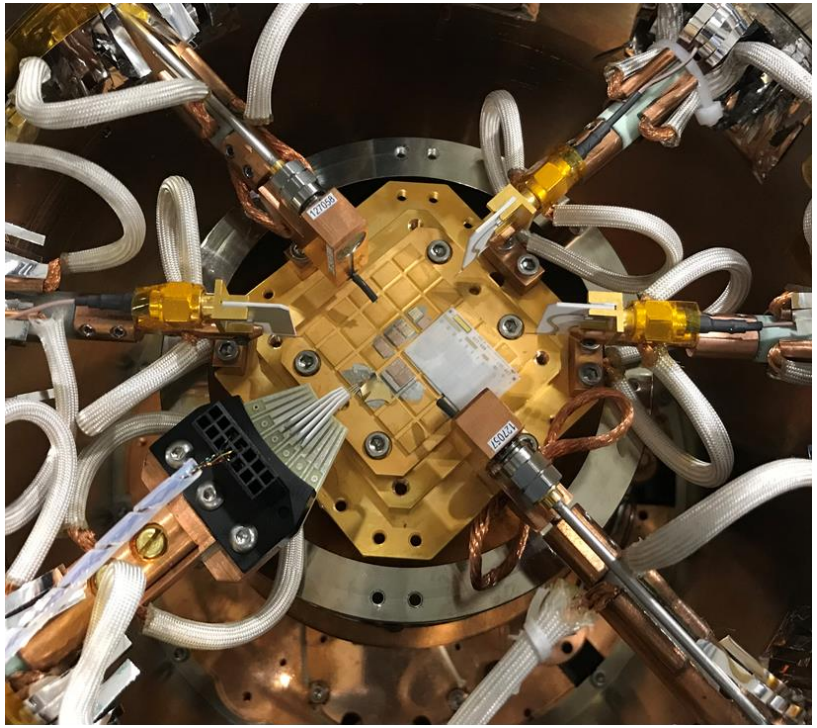
4 K open measurement following wafer-level calibration — ~2 hours between curves

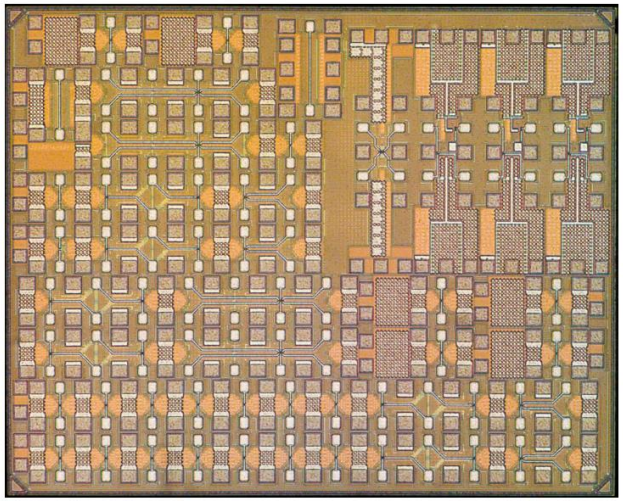


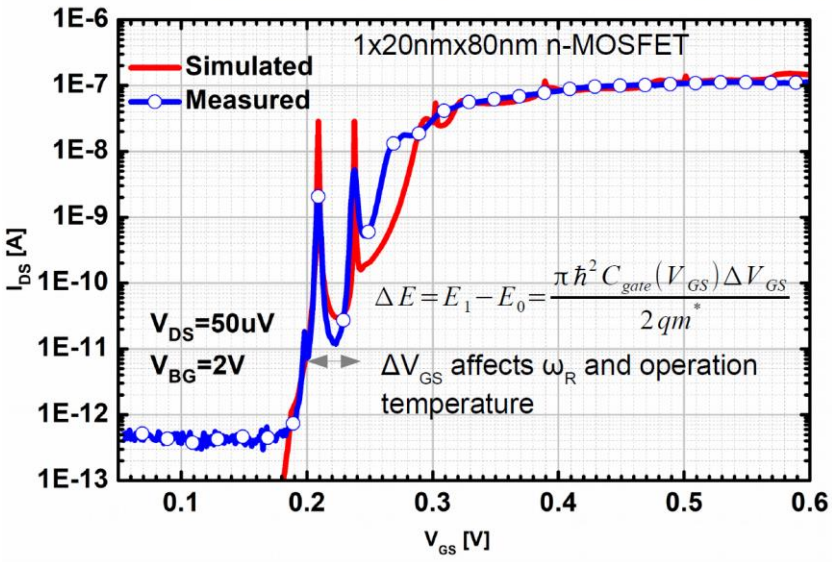
Lake Shore work with FormFactor

Monolithic quantum computing ICs

- 2 K sample stage temperature
- Integration of 67 GHz microwave probe, low-leakage DC transport measurements & multiple DC bias pins for gating
- Future: with magnetic field & 140 GHz probing





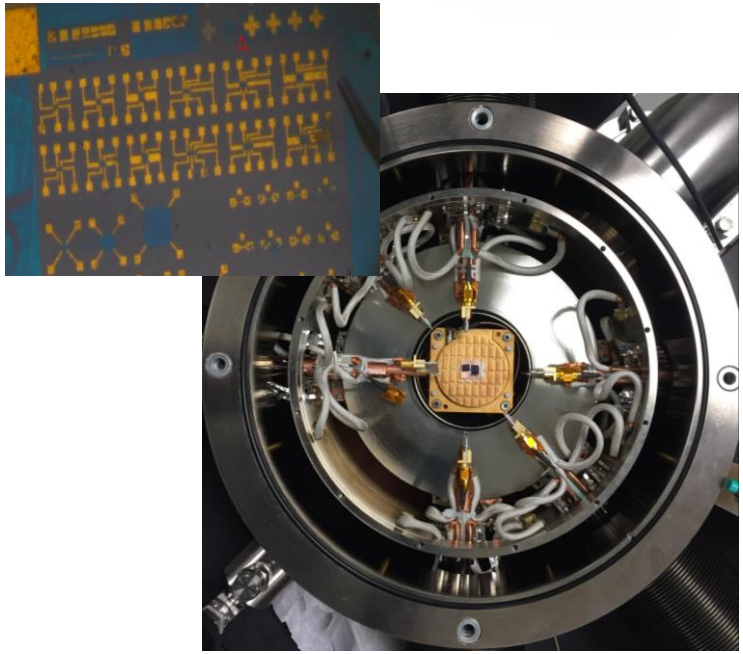


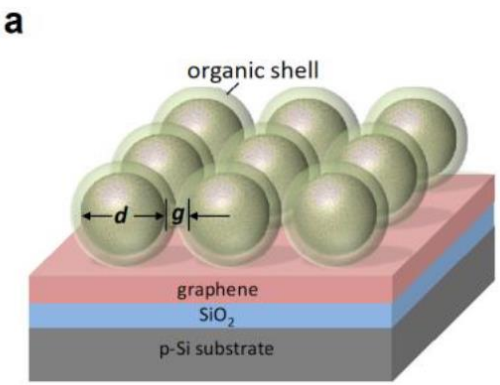
"Cryogenic Characterization of 22-nm FDSOI CMOS Technology for Quantum Computing ICs", IEEE EDL (2019).

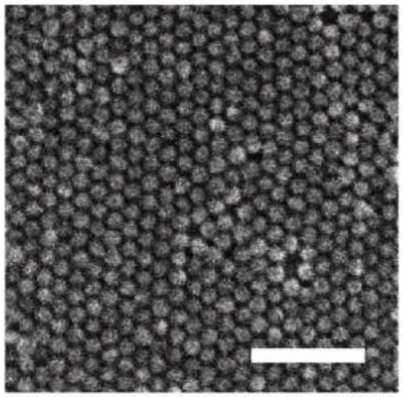
Lake Shore CRYOTRONICS

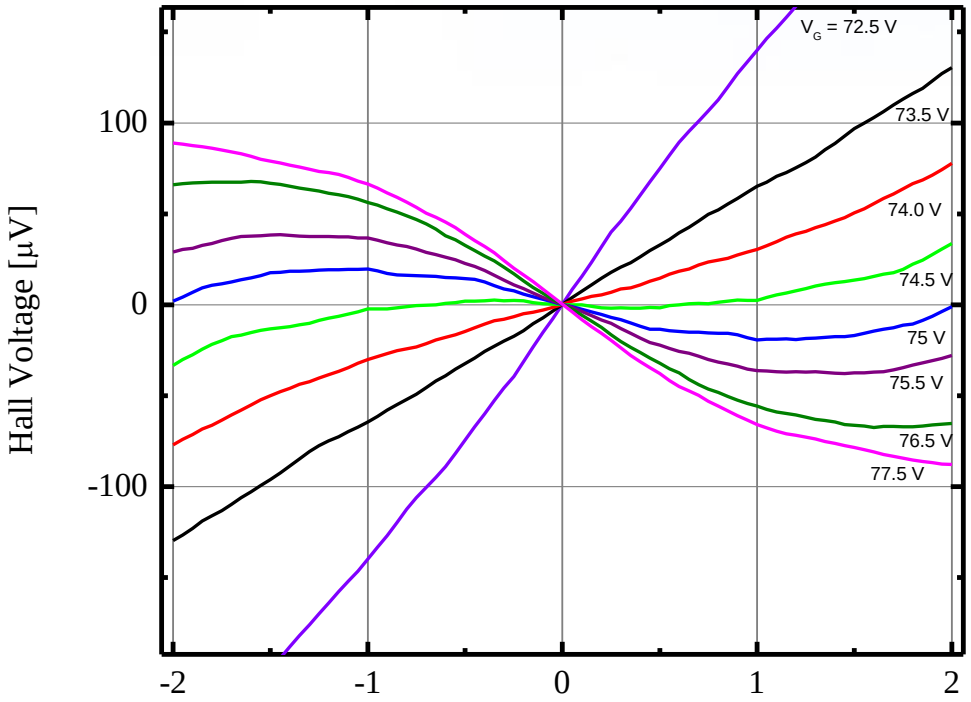
Wafer-level, gated Hall effect measurement

- Functionalized graphene
- 4- and 6-terminal Hall measurements
- Backside gating
- Proximity-induced ferromagnetism









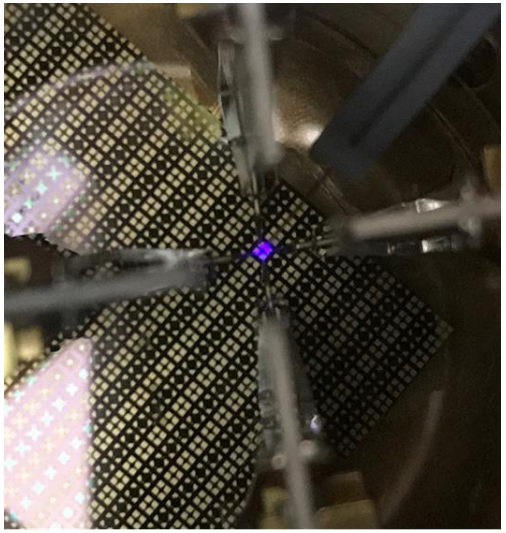
Nanoparticle-Induced Anomalous Hall Effect in Graphene, Nano Lett. (2019)

Lake Shore CRYOTRONICS

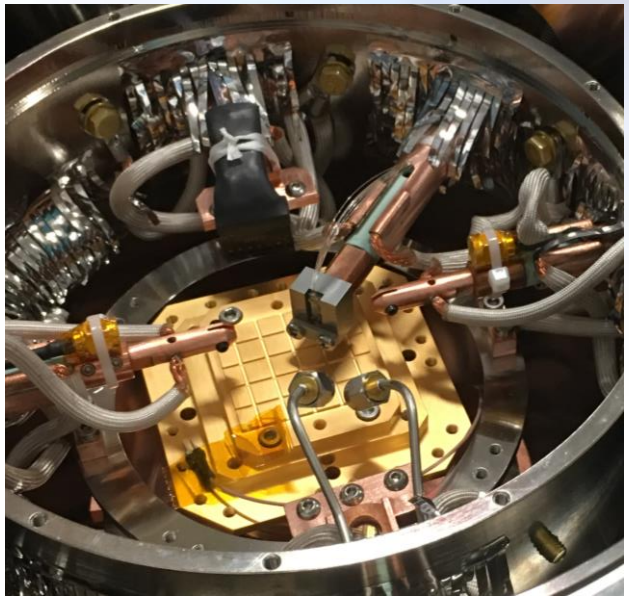
Fiber optic solutions

Illumination

- UV-VIS, IR-VIS multimode
- Single mode & PM fiber
- Specials
  - Lensed
  - Solarization Resistant
  - Mid-IR

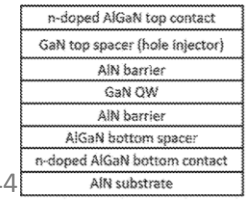


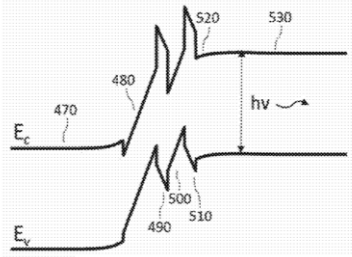
Integration

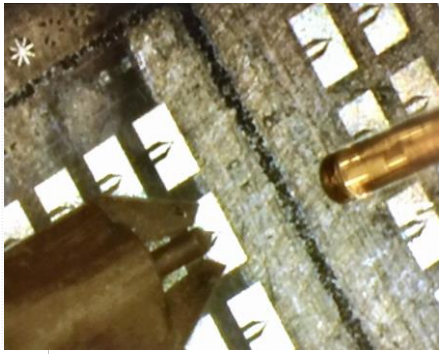


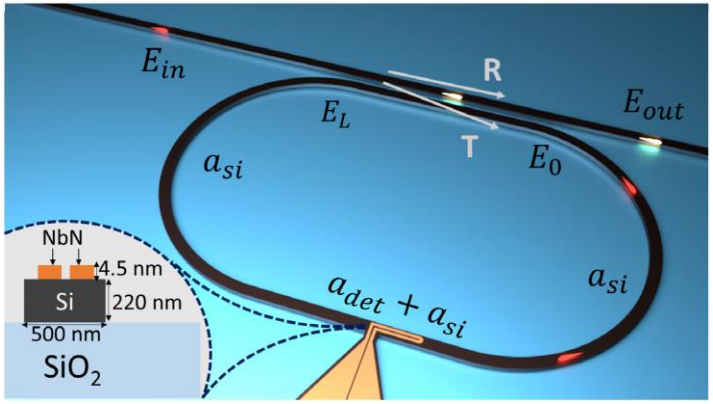
Collection

- UV-VIS, IR-VIS multimode









Lake Shore CRYOTRONICS

Summary

- Why use a probe station
- How:
  - Tailor the probes to the application
  - Use triaxial cabling for low current measurements
  - Mount your sample wafer appropriately
- What:
  - Transistor IV curves
  - Hall effect measurements (magnetic field)
  - Optical excitation and collection