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United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

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Workshop on Topics in Quantum Turbulence

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Producing and Probing Quantum Turbulence

G. Ihas
University of Florida
Dept. of Physics
Gainesville
U.S.A.

Producing and Probing Quantum Turbulence
ICTP Trieste March 16, 2009

Gary Ihas

University of Florida

University of Birmingham

Lancaster University

Solid State Institute-Kiev

Funding: EPSRC, Research Corporation and US NSF

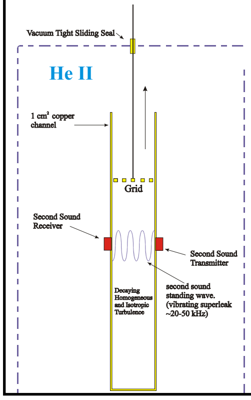
Contributors: **Kyle Thompson, Ho Bun Chan, Corey Stambaugh, Ivan Lozano, G. Labbe, S-c. Liu, R. Adjimambetov, M. Padron, V. Mitin, W.F. Vinen, Mark Giltrow, P.V.E. McClintock, D. Charalambous, P.C. Hendry**

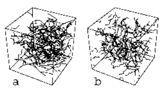
Today's Talk

- Grid turbulence in ^{4}He
- High T > 1K
- Low T < 600 mK
  - Vibrating grids
  - Pulled grids-method of motation
- Probes
  - Temperature
  - Pressure

Grid Turbulence

Stalp Apparatus





quantum of circulation:
$\kappa = h/m_4 \sim 10^{-3} cm^2 s^{-1}$ (n=1)

L = length of quantized vortex line per unit volume.

$\omega_s = \kappa L$ = total rms superfluid vorticity

$\ell = L^{-1/2}$ = average inter-vortex line spacing.

$E_v = \frac{\rho_s \kappa^2}{4\pi} \ln\left(\frac{r_{eff}}{a_0}\right)$ ($\sim 10^{-7}$ erg cm^{-1}, $a_0 \sim 0.1$ nm, $r_{eff} \sim \ell$)

Stalp Second Sound Apparatus

Second Sound and NMR

- Second sound, used successfully to measure vortex line density in ^{4}He, does not propagate below 1 K in ^{4}He or in superfluid ^{3}He.

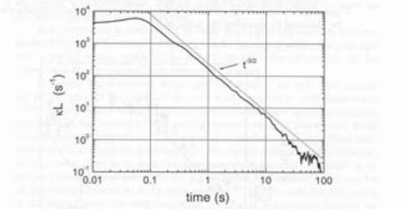


Fig. 7. The observed decay of vortex line density behind a towed grid. From thesis of S.R. Stalp (University of Oregon).

- However, NMR signals can be used to measure vortex densities in ^{3}He, with very high sensitivity.

As T→0

There is much interest in quantum turbulence in ^{4}He and ^{3}He-B at temperatures where the density of normal fluid is negligible.

No viscosity so—

Richardson/Kolmogorov cascade can not account for turbulence decay.

Experiments to do

The search for appropriate experimental techniques for this temperature range poses major challenges:

- Ion trapping
- Bubble states formed from triplet state He_2 molecules
- Miniature pressure and temperature sensors are being developed.

More Experiments

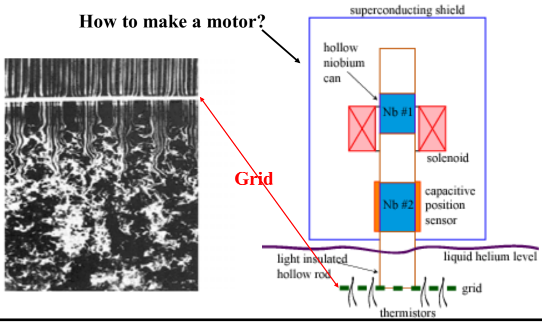
- Calorimetry: At very low temperatures the thermal energy in a superfluid can be very small, especially in ^{4}He. This means that turbulent energies can be comparable with the thermal energy.

  Two consequencies:
  - Decay of turbulence can be monitored by observing rise in temperature (good).
  - Continuous maintenance of steady-state turbulence is impossible (bad, because gain in sensitivity in a transducer from time-averaging is ruled out).
  - No steady flow
- Andreev reflection of thermal quasi-particles in ^{3}He-B by turbulent velocity fields. Quantitative measurements of vortex densities and the spatial distribution of vortices in ^{3}He-B possible at very low temperatures.

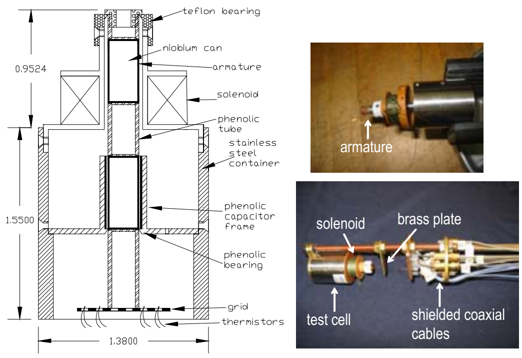
We want to study turbulence which has been well characterized classically and comparable to theory and simulations

B: Homogeneous Isotropic Turbulence

Pull grid at constant velocity



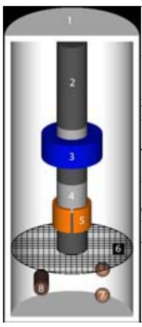
First Realization of Florida Motor



Creating Turbulence in a Dissipationless Fluid

Gary G. Ihas (University of Florida) DMR-Award # 0602778

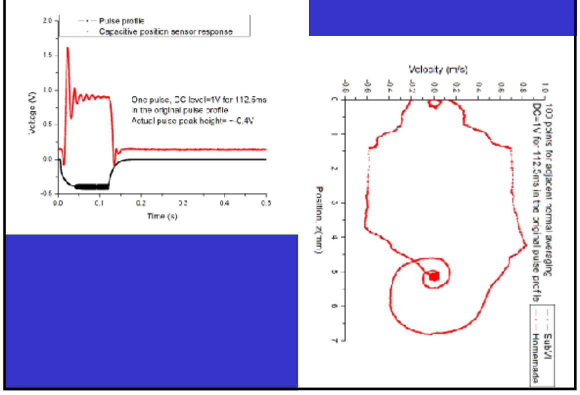
If we pull a wire mesh through a fluid with zero viscosity, we might think that there will be no drag force and that the fluid will smoothly flow around the wires of the mesh, creating no turbulence. Yet, turbulence of sorts has been observed in liquid helium near absolute zero, which has vanishingly small viscosity. Once this turbulence is created, it seems that there is no mechanism except through viscosity for it to decay. Yet again, it does decay. Until now, no one had succeeded in producing isotropic homogeneous turbulence, as is often studied in classical fluids, in a dissapationless fluid. We have designed, built, and operated the superconducting pulsed actuator (shown schematically at right), which, when mounted on a dilution refrigerator, allows exactly such studies to be achieved.



Schematic of Cell

1. Pb plated Cu cell
2. Phenolic armature
3. Superconducting solenoid
4. Superconducting Nb can (2)
5. Capacitive position sensor
6. Mesh grid
7. 300 µm thermistors
8. Resistive heater

Position Sensor-Motor Motion

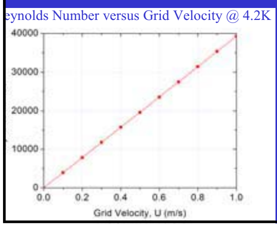


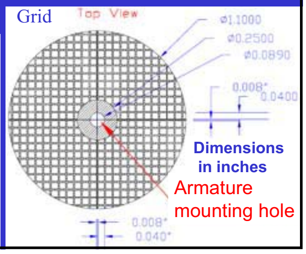
Grid Reynolds Number Re_m at 4.2 K

Grid has 1 mm square holes

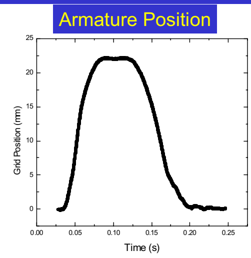
$$R_e = \frac{UL}{\nu} = \frac{\text{inertial force}}{\text{viscosity force}} = \frac{U \times 1\times10^{-3}\, m}{2.6\times10^{-8}\, m^2\cdot s^{-1}}$$

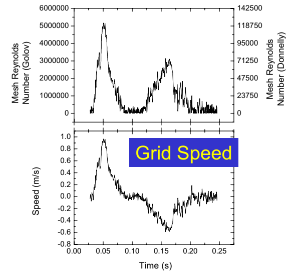
$$= 3.9\times10^{4} \times U \text{ (units in m/s) at 4.2K in liquid helium}$$





Actual Armature Motion and Mesh Reynolds Number Re_m





Grid turbulence experiments

Apparatus size and mesh Reynolds numbers R_M

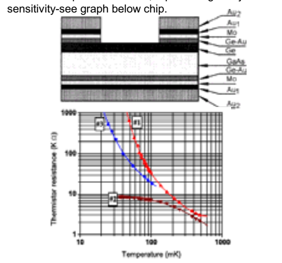
Source	test section	max R_M (million)
Kistler & Vrebalovich (1966) (air at 4 atmospheres)	2.6 m × 3.5 m	2.3
Comte-Bellot & Corrsin (1971) (atmospheric air)	1 m × 1.3 m	0.3
Oregon towed grid (He II)	1 cm × 1 cm	0.5
Yale towed grid (He I)	5 cm × 5 cm	0.8
UF (He II)	2.8 cm x 28 cm	0.1 or 5

Detecting Turbulence in Helium near T=0: Thermometry

Gary G. Ihas (University of Florida), DMR-Award # 0602778

One goal of hydrodynamic research is to study very large phenomena, such as hurricanes and sun spots, in the laboratory by constructing a system which scales from millions of meters in size to one meter in the lab, retaining the same type of flows, such as turbulence. Liquid and cryogenic (very cold) gaseous helium enable this scaling because their viscosities, a key parameter governing turbulence, may be varied from that similar to air to essentially zero. But measurements at these temperatures require the development of new sensors that function in this cold environment. We have developed extremely small electrical resistance thermometers which have a fast reaction time (less than 1/10 sec.) and adjustable sensitivity for use from 10 mK to 5 K. They measure both ambient temperature and temperature fluctuations prevalent in turbulent flow.

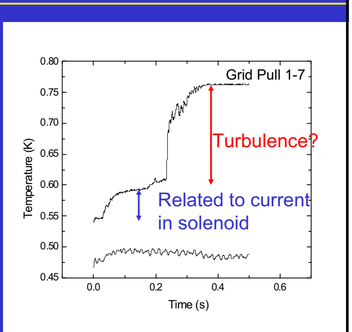
Cross section of thermometer-made using computer chip technology. Ge (Germanium) layer is active element, deposited on GaAs substrate. Heat treatment cause various amounts of Ga and As to become dopants in Ge, producing adjustable sensitivity-see graph below chip.



Back to Pulled Grid Data at 0.52 K

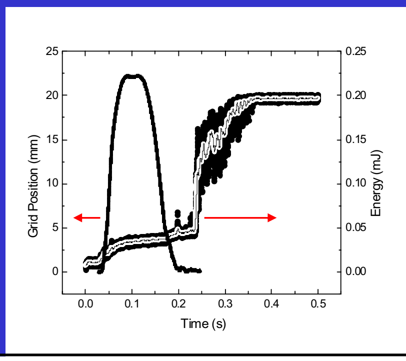
Temperature rise for the cases where motor moved (top) and motor did not move (bottom)

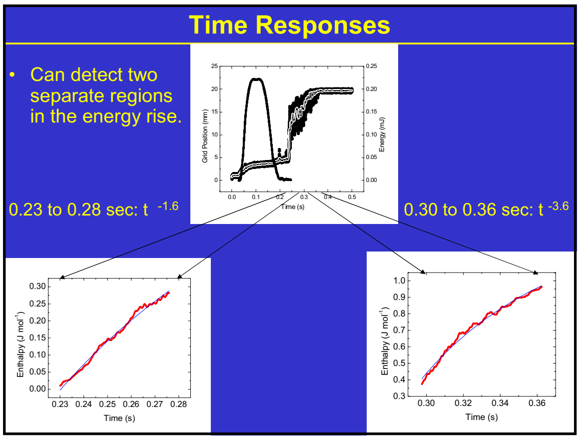
- Both have an initial rise thought to be electronic.
- Grid motion causes large T rise

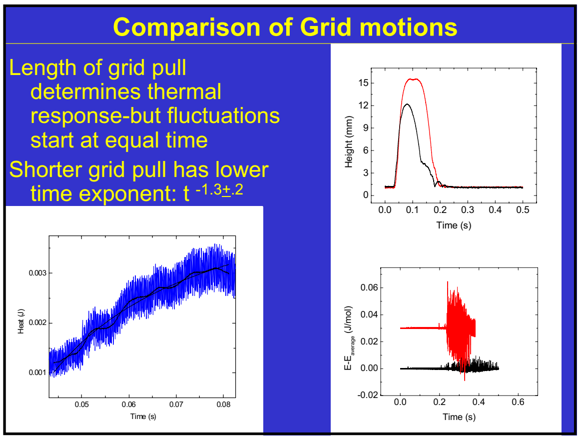


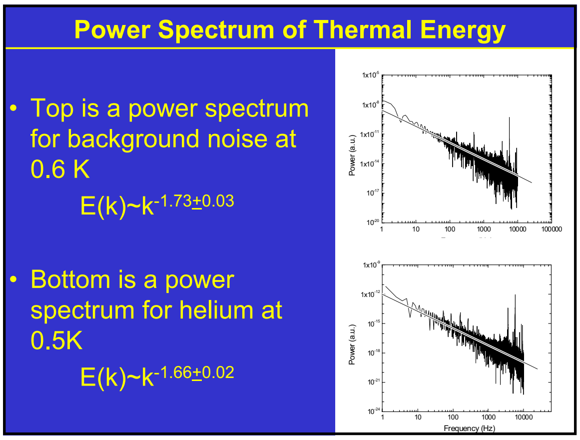
Grid Motion—>Energy Rise

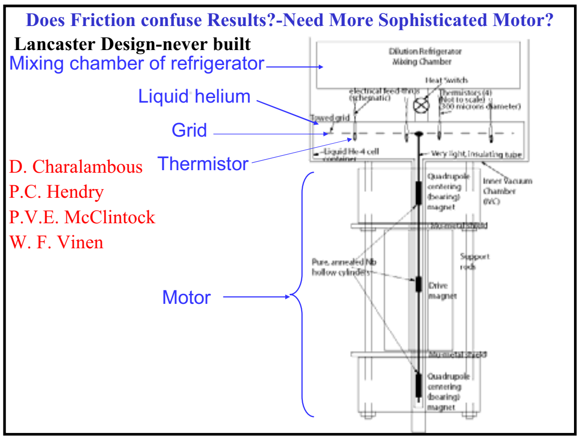
Motor stops moving followed by a rise in energy

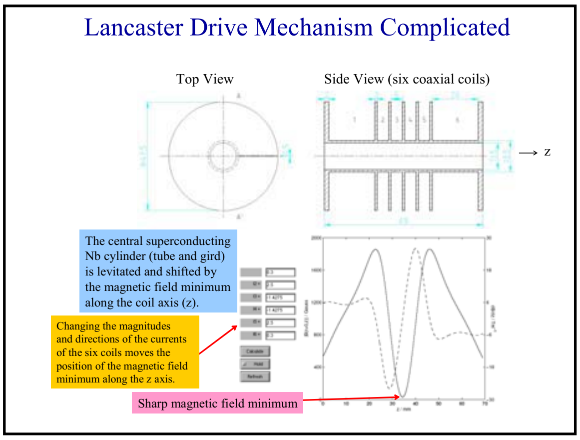


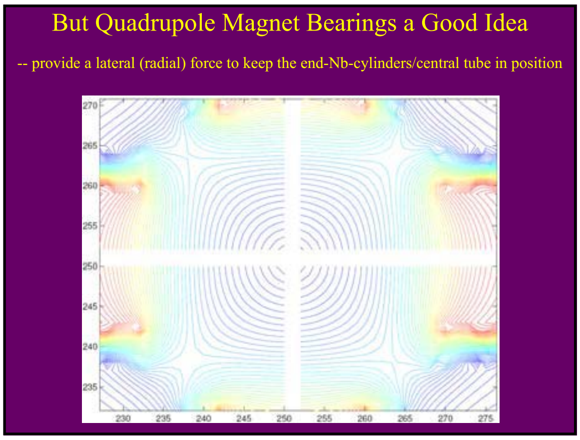

Time Responses
Can detect two separate regions in the energy rise.
0.23 to 0.28 sec: t -1.6
0.30 to 0.36 sec: t -3.6
Grid Position (mm)
Energy (mJ)
Time (s)
Enthalpy (J mol-1)
Time (s)


Comparison of Grid motions
Length of grid pull determines thermal response-but fluctuations start at equal time
Shorter grid pull has lower time exponent: t -1.3±.2
Height (mm)
Time (s)
Heat (J)
Time (s)
E-E average (J/mol)
Time (s)

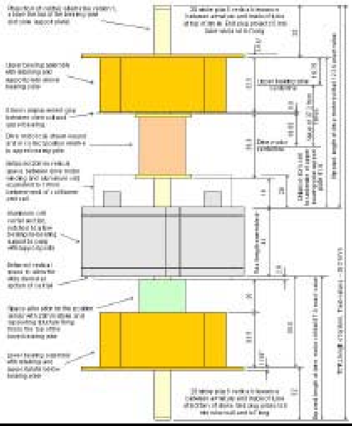

Power Spectrum of Thermal Energy
Top is a power spectrum for background noise at 0.6 K
E(k)~k-1.73±0.03
Bottom is a power spectrum for helium at 0.5K
E(k)~k-1.66±0.02
Power (a.u.)
Frequency (Hz)


Does Friction confuse Results?-Need More Sophisticated Motor?
Lancaster Design-never built
Mixing chamber of refrigerator
Liquid helium
Grid
Thermistor
Motor
D. Charalambous
P.C. Hendry
P.V.E. McClintock
W. F. Vinen
Dilution Refrigerator Mixing Chamber
Heat switch
Quadrupole centering (bearing) magnet
Inner Vacuum Chamber (IVC)
Support rods
Drive magnet
Pure, annealed Nb hollow cylinders
Very light, insulating tube

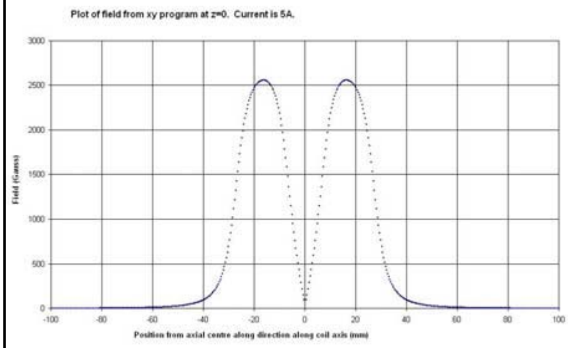

Lancaster Drive Mechanism Complicated
Top View
Side View (six coaxial coils)
→ z
The central superconducting Nb cylinder (tube and grid) is levitated and shifted by the magnetic field minimum along the coil axis (z).
Changing the magnitudes and directions of the currents of the six coils moves the position of the magnetic field minimum along the z axis.
Sharp magnetic field minimum


But Quadrupole Magnet Bearings a Good Idea
-- provide a lateral (radial) force to keep the end-Nb-cylinders/central tube in position

New Florida Birmingham Lancaster Motor (Details Secret!)



Bearing Magnetic Field



Need Probe of Vorticity-- requirements

- Length scales: wide range of scales from the size of the flow obstacle or channel giving rise to the turbulence to the (small) scale on which dissipation occurs.
  - E.g. turbulence in ^{4}He above 1K has energy-containing eddies of 1 cm and characteristic velocity 1 cm s^{-1}. Below 1K Kelvin wave cascade (Vinen) to dissipate energy may take smallest scale to 10 nm.
- Time scales: ranges from 1 s to a few milliseconds.
- Velocity correlation functions: play an important role in classical turbulence (structure functions). We could derive energy spectra from them and look for deviations from Kolmogorov scaling (higher-order structure functions).

Localized probes

- Want probes (other than PIV and LDV) that measure local properties (such as pressure, velocity). Ideally we need a spatial resolution of at least 30 microns and a frequency response to at least 1 kHz.
- Hot wire anemometers do not work in ^{4}He owing to the high thermal conductivity. Could they work in ^{3}He?
- A pressure transducer with a spatial resolution of about 1 mm and good frequency response was used in an important experiment by Maurer and Tabeling.
- We are pursuing smaller pressure transducers based on micro-fabrication techniques.

Calorimetry Probe Development

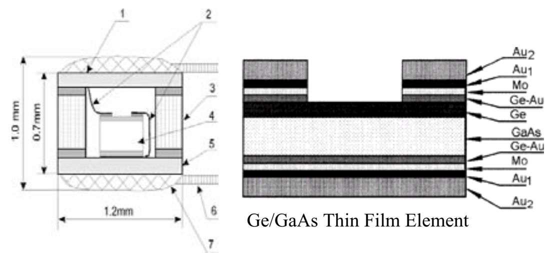
Thermistor Characteristics

- Operating temperature: 10 – 100 mK
- Sensitivity: δT ~ 10^{-4} mK
- Short response time: ~ 1 ms
- Small mass & good thermal contact.
- Ease of manufacture

Use computer chip fabrication technique: V. Mitin
http://microsensor.com.ua/products.html

Sensor Package Construction

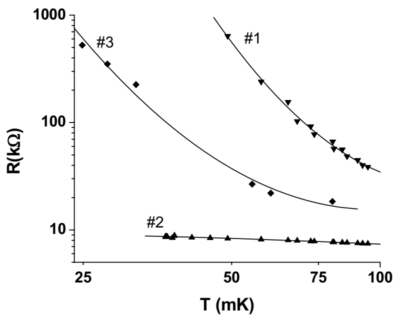
- Ge/GaAs thermistors **300 μm** square by **150 μm** thick.



Ge/GaAs Thin Film Element

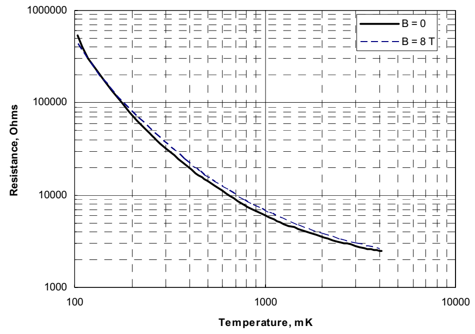
1 and 5: copper discs; 2: gold strip; 3: corundum cylinder; 4: Ge/GaAs sensitive element; 6: copper wire; 7- tin.

Thermistor R vs. T already used and shown

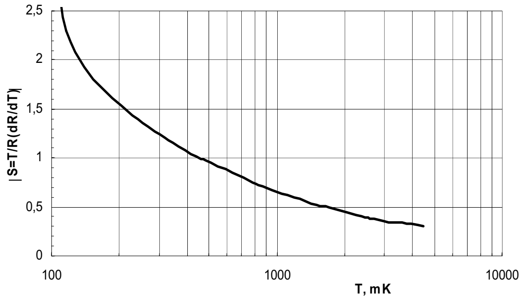


Tune characteristics by heat treatment

New Thermistors designed for the Job!



Sensitivity



$$\left(\frac{dR}{dT}\right)_{100mK} = \frac{500k\Omega}{100mK}\bullet 3 = 15\frac{\Omega}{\mu K}$$

Our resolution at 1 msec
5 ohms

Another Probe

Pressure Transducer Requirements

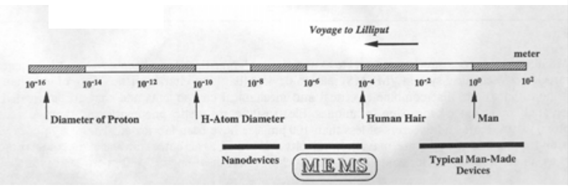
- sampling on (100) micron scale
- sensitivity: 100 Pascal
- fast: 1 msec
- function at low temperatures (20 – 100 mK)
- transduction: as simple as possible

MEMS Technology Pressure Sensors

- Piezo-resistive
- Capacitive
- Optical

MEMS Technology

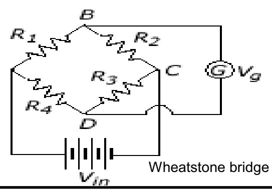
Perfect size range



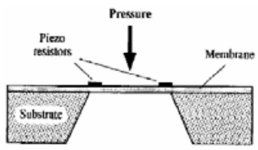
First try commercial devices

Design Of Piezo-resistive Pressure Sensors

- Typical design: 4 piezo-resistors in Wheatstone bridge on a diaphragm
- diaphragm deflects from applied pressure causing the deformation of the piezo-resistors mounted on the surface



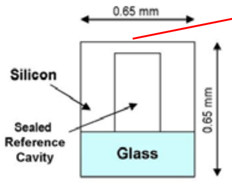
Wheatstone bridge

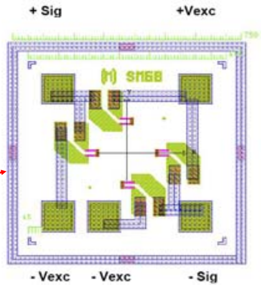


Piezo-resistive Pressure Sensor SM5108

Semiconductor resistors joined by aluminum conductors in bridge configuration

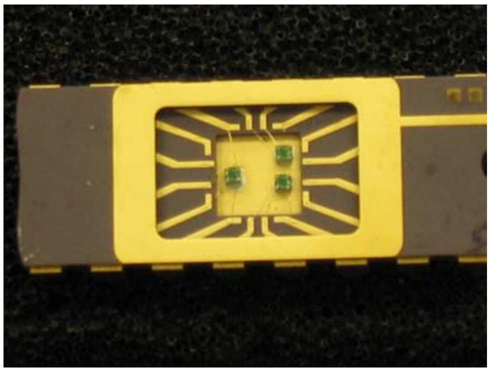
Resistors placed on diaphragm
Two strained parallel to I
Two strained perpendicular to I





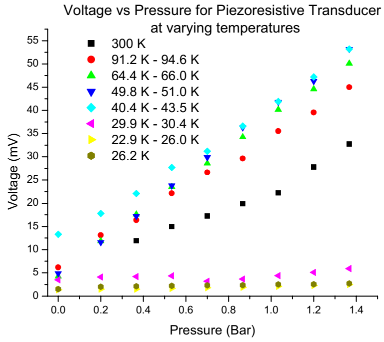
Manufactured by Silicon Microstructures, Inc.

Piezo-resistive Pressure Sensors SM5108 on Test Header

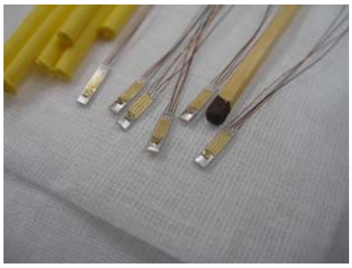


Drawbacks of Piezo-resistive Pressure Sensors-Results

- Relatively low sensitivity
- Large temperature dependence temperature compensation necessary



Piezo Resistive Transducers made to work at Low T

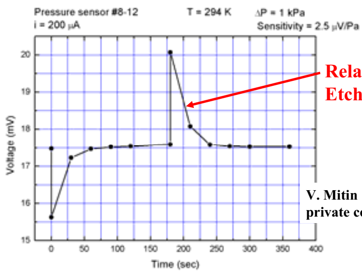


Properly Doped Germanium

V. Mitin
private communication

Resistances vs. T and Response to ΔP of Germanium Sensors

#	Dimensions in mm	R (294 K) kOhms	R (77.4 K) kOhms	R (4.2 K) kOhms
8-2	1x1	1.6	24.6	35.1
8-4	1*1	0.5	14.0	18.5



Relaxation thru Etching orifice

V. Mitin
private communication

Commercial Pressure Transducers Hearing Aids

A Piezoelectric Transducer for a Hearing Aid Using PZT Thin Film.

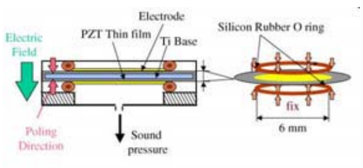
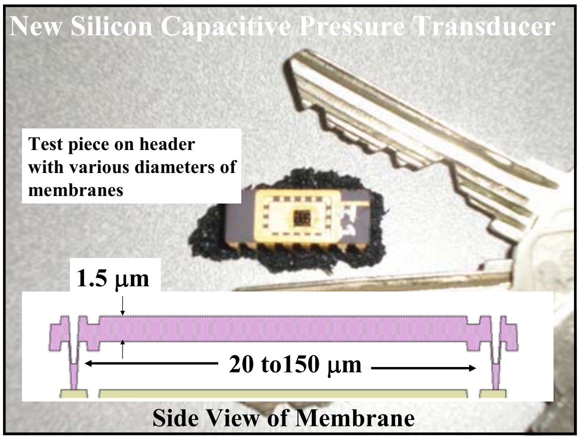
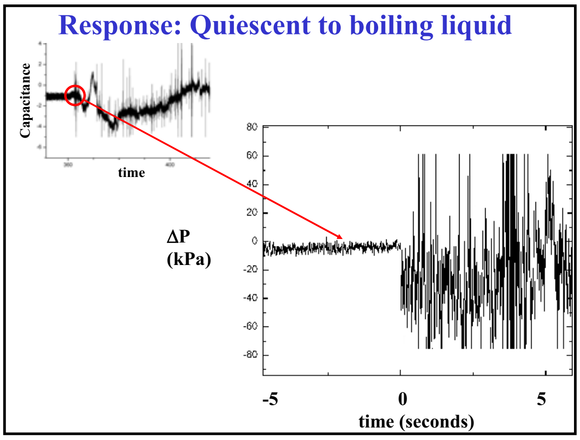


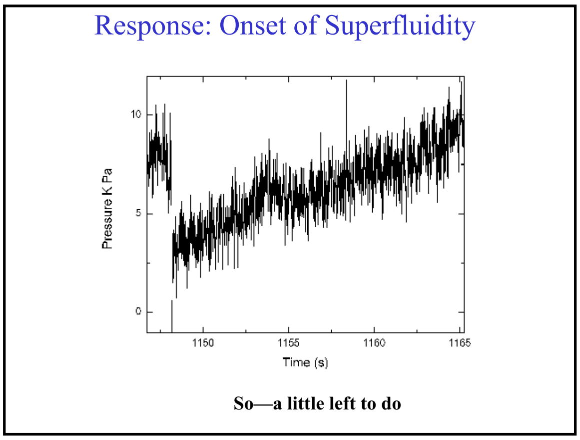
Fig. 3 The bimorph construction of the diagram and its mounting.

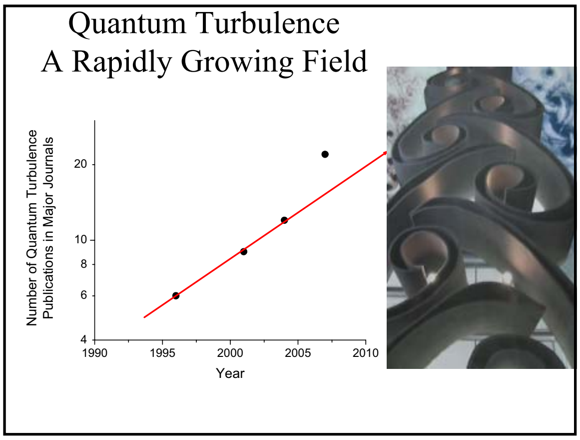
Like all pressure transducers designed for use at room temperature, this must be modified or is just unusable at low temperature.
It is too large and has rubber gaskets which would freeze.

http://www.aml.t.u-tokyo.ac.jp/research/earphone/earphone_e.html


New Silicon Capacitive Pressure Transducer
Test piece on header with various diameters of membranes
1.5 µm
20 to150 µm
Side View of Membrane


Response: Quiescent to boiling liquid
Capacitance
time
ΔP (kPa)
80
60
40
20
0
-20
-40
-60
-80
-5
0
5
time (seconds)


Response: Onset of Superfluidity
Pressure K Pa
10
5
0
1150
1155
1160
1165
Time (s)
So—a little left to do


Quantum Turbulence
A Rapidly Growing Field
Number of Quantum Turbulence Publications in Major Journals
20
10
8
6
4
1990
1995
2000
2005
2010
Year