Germanium: From Its Discovery to High Speed Transistors

E.E. Haller

UC Berkeley & LBNL

EECS Solid State Seminar

March 18, 2011

Topics to be discussed

- Discovery of Germanium and Early History
- From the “Physics of Dirt” to a Respectable Science
- Point Contact Diodes and Transistors
- Applications of Germanium in Nuclear Physics: GeLi and High-Purity Ge detectors
- New Physics with Ultra-Pure Germanium
- Infrared Photoconductors and Bolometers
- Isotopically Controlled Germanium
- Germanium Speeds Up Silicon Transistors

Anno 1886

- Discovery of a new element in the IVth column: Germanium by Clemens Winkler: C. Winkler, "Mittheilungen über das Germanium," J. für Prakt. Chemie **34**(1), 177-229 (1886)
- The first 4-wheel motor car by Daimler & Benz
- Coca-Cola is formulated in Atlanta by a pharmacist
- Walter Schottky is born, the future father of the metal-semiconductor theory
- Elemental Fluorine is isolated by Moisson
- Patents are filed in the US and Great Britain for the mass production of Aluminium

D.I. Mendelejev and C.A. Winkler at the meeting of the 100th anniversary of the Prussian Academy of Science, Berlin, March 19, 1900.

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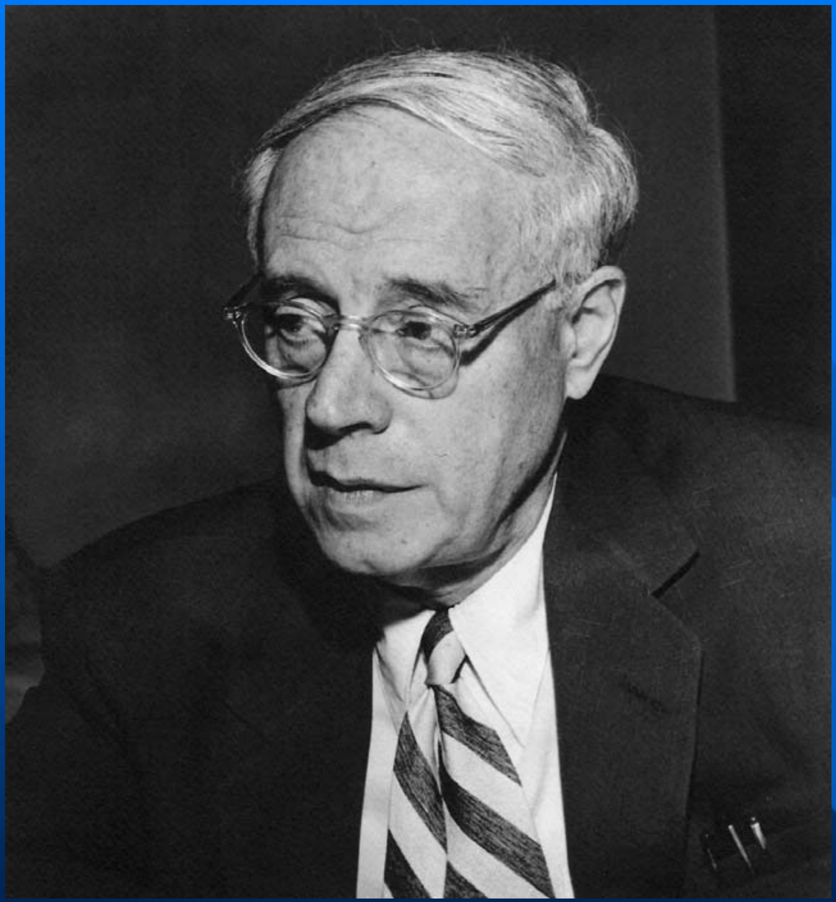
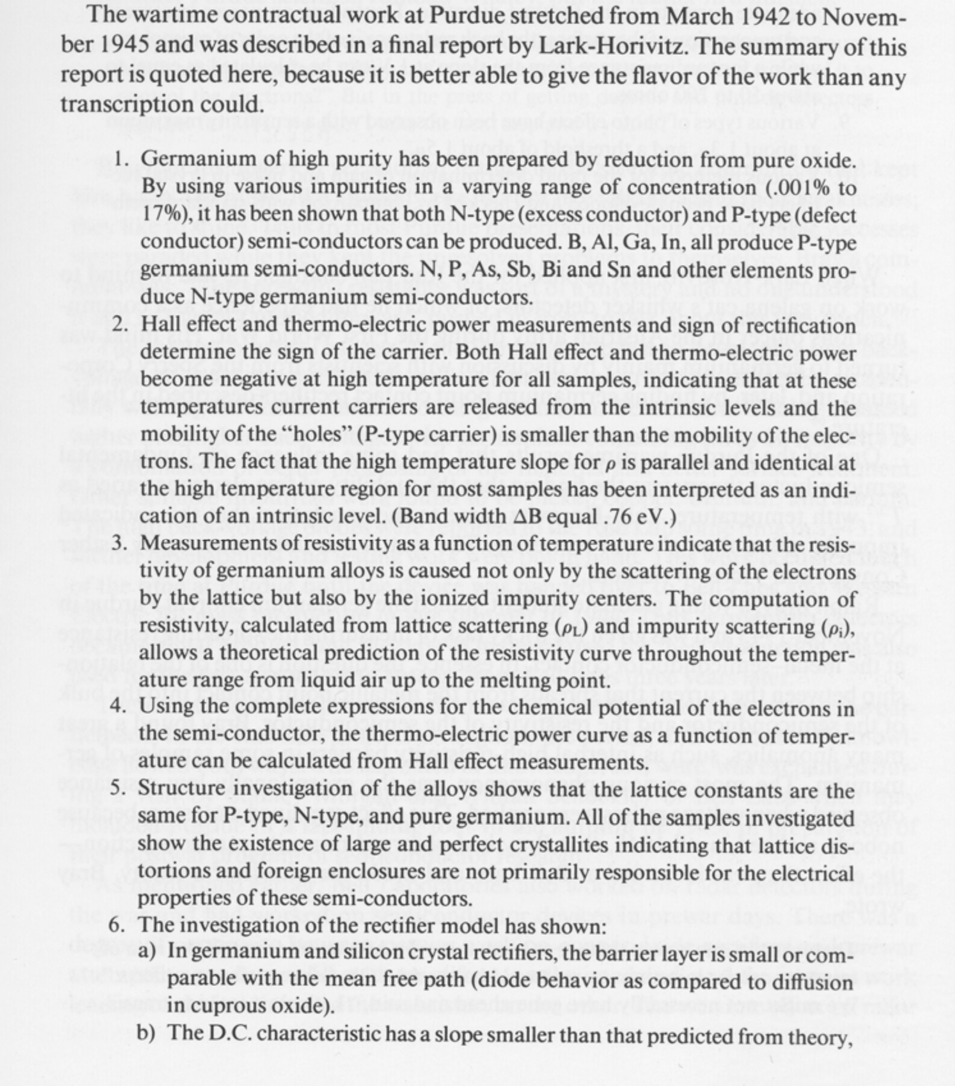
From the "Physics of Dirt" to a Respectable Science



Karl Lark-Horovitz joined the Physics Dept., Purdue University in 1929. In 1942 he made the fateful decision to work on ***Germanium***, not on Galena (PbS) or Silicon. The first transistor was built at Bell labs with a slab of Purdue Germanium! Based on the Purdue work, Germanium became the first controlled and understood semiconductor.

Purdue University Results

Karl Lark-Horovitz



The wartime contractual work at Purdue stretched from March 1942 to November 1945 and was described in a final report by Lark-Horivitz. The summary of this report is quoted here, because it is better able to give the flavor of the work than any transcription could.

1. Germanium of high purity has been prepared by reduction from pure oxide. By using various impurities in a varying range of concentration (.001% to 17%), it has been shown that both N-type (excess conductor) and P-type (defect conductor) semi-conductors can be produced. B, Al, Ga, In, all produce P-type germanium semi-conductors. N, P, As, Sb, Bi and Sn and other elements produce N-type germanium semi-conductors.
2. Hall effect and thermo-electric power measurements and sign of rectification determine the sign of the carrier. Both Hall effect and thermo-electric power become negative at high temperature for all samples, indicating that at these temperatures current carriers are released from the intrinsic levels and the mobility of the "holes" (P-type carrier) is smaller than the mobility of the electrons. The fact that the high temperature slope for ρ is parallel and identical at the high temperature region for most samples has been interpreted as an indication of an intrinsic level. (Band width ΔB equal .76 eV.)
3. Measurements of resistivity as a function of temperature indicate that the resistivity of germanium alloys is caused not only by the scattering of the electrons by the lattice but also by the ionized impurity centers. The computation of resistivity, calculated from lattice scattering (ρ_L) and impurity scattering (ρ_i), allows a theoretical prediction of the resistivity curve throughout the temperature range from liquid air up to the melting point.
4. Using the complete expressions for the chemical potential of the electrons in the semi-conductor, the thermo-electric power curve as a function of temperature can be calculated from Hall effect measurements.
5. Structure investigation of the alloys shows that the lattice constants are the same for P-type, N-type, and pure germanium. All of the samples investigated show the existence of large and perfect crystallites indicating that lattice distortions and foreign enclosures are not primarily responsible for the electrical properties of these semi-conductors.
6. The investigation of the rectifier model has shown:
   a) In germanium and silicon crystal rectifiers, the barrier layer is small or comparable with the mean free path (diode behavior as compared to diffusion in cuprous oxide).
   b) The D.C. characteristic has a slope smaller than that predicted from theory,

Purdue University Results

a fact which can be explained by the assumption of a distribution of contact potentials at the surface of the semi-conductors (multi-contact theory).

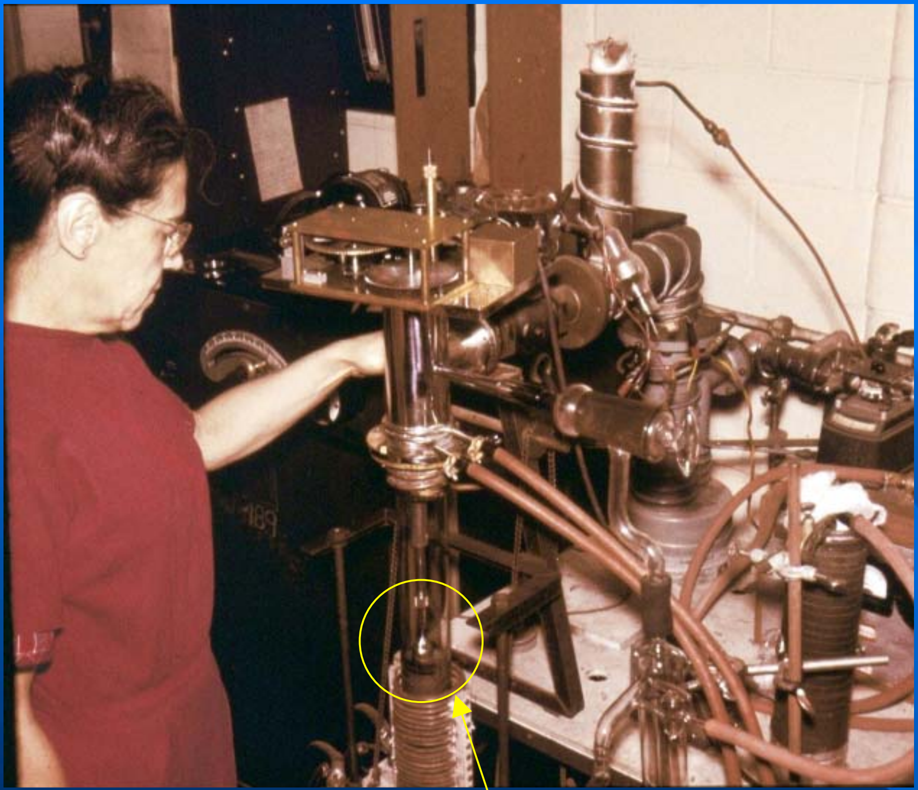
c) The behavior of spreading resistance and contact capacity in germanium crystals indicates that the present model used to calculate high frequency performance is oversimplified and cannot explain the measurements.

d) Experiments with germanium rectifiers in a high vacuum or in controlled atmospheres show that while rectification exists in a high vacuum, a change in atmosphere produces adsorbed layers which may greatly influence the shape of the D.C. characteristics.

7. Germanium semi-conductors containing P or Sb can be used in microwave mixer crystals, comparing well in performance to silicon crystals.
8. Sn or N added to germanium produces crystal detectors which withstand a high voltage in the order up to 250 V or more in the back direction, while passing adequate currents in the forward direction. Depending on power treatment and preparation of the surface, the back resistance is of the order of megaohms, while a forward resistance from the slope at 1 V can be calculated as equal to about 50 to 200 ohms.
9. Various types of photo effects have been observed with a sensitivity maximum at about 1.3μ, and a threshold of about 1.5μ.
10. Various methods for the rapid determination of gain and noise in crystal rectifiers have been developed and checked by comparison with standard methods.[65]

When Lark-Horovitz first applied for the Rad Lab contract, he had in mind to work on galena cat's whisker detectors, of which he had experience as a communications officer in the Austrian army during the First World War. His mind was turned to germanium mainly by discussion with scientists from the Sperry Corporation and, later, by finding germanium point contact rectifiers described in the literature.[66]

Purdue University Researchers



Louise Roth

Ge single crystal

Anant K. Ramdas

(50th anniversary!)

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Point Contact Diodes and Transistors

- How to detect the weak radar pulse echoes?
- Cat's whisker metal point contacts to polycrystalline Ge and Si formed diodes sufficiently fast to work as mixers for radar reception in WWII
- "Tapping" rectifiers to optimize their performance

The MIT Radiation Laboratory

CRYSTAL RECTIFIERS

By HENRY C. TORREY
ASSOCIATE PROFESSOR OF PHYSICS
RUTGERS UNIVERSITY

And CHARLES A. WHITMER
ASSOCIATE PROFESSOR OF PHYSICS
RUTGERS UNIVERSITY

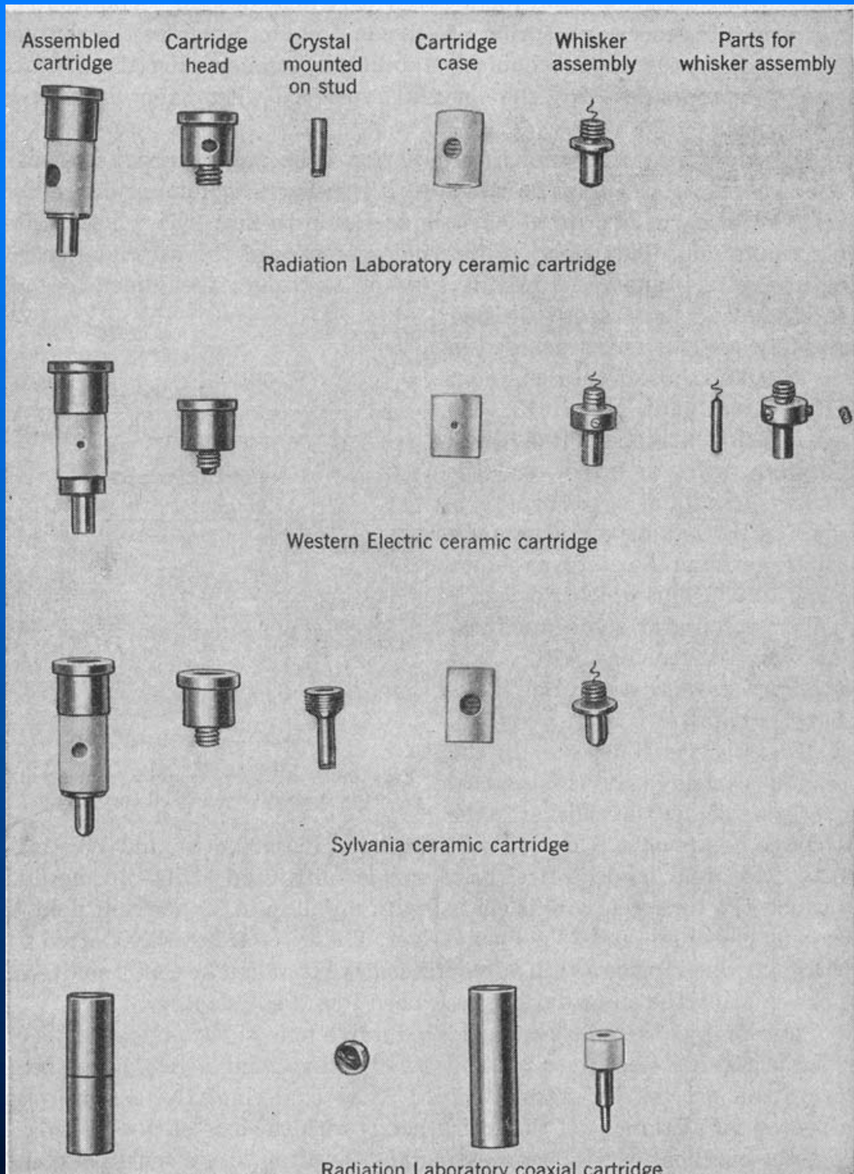
EDITED BY

S. A. GOUDSMIT — LEON B. LINFORD
JAMES L. LAWSON — ALBERT M. STONE

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
NATIONAL DEFENSE RESEARCH COMMITTEE

NEW YORK AND LONDON
MCGRAW-HILL BOOK COMPANY, INC.
1948

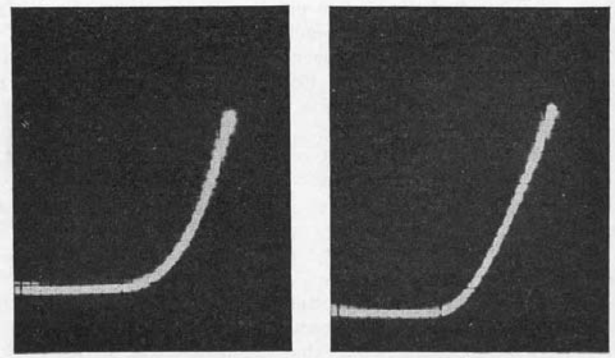
The title page of MIT's Radiation Laboratory Series Volume 15.
This series gives a detailed account of the Radar R&D activities at MIT during WWII.



fier C in series with the resistor R. A suitable value of R is 10 to 20 ohms.

Once contact is established, the pressure is increased until a predetermined characteristic is observed on the oscilloscope. In this stage the front resistance, measured at a few tenths of a volt, is between 300 and 400 ohms, and the back resistance is about 10,000 ohms. The cartridge is then "tapped"[1] lightly. Judicious tapping causes the front resistance to drop to between 200 to 300 ohms and the back resistance to increase to between 20,000 to 100,000 ohms. (These values are for an applied potential of a few tenths of a volt.) Before tapping, the oscillo-

!



(a) (b)

FIG. 10.12.—D-C characteristic curve as seen on an oscilloscope. (a) Before tapping; (b) after tapping.

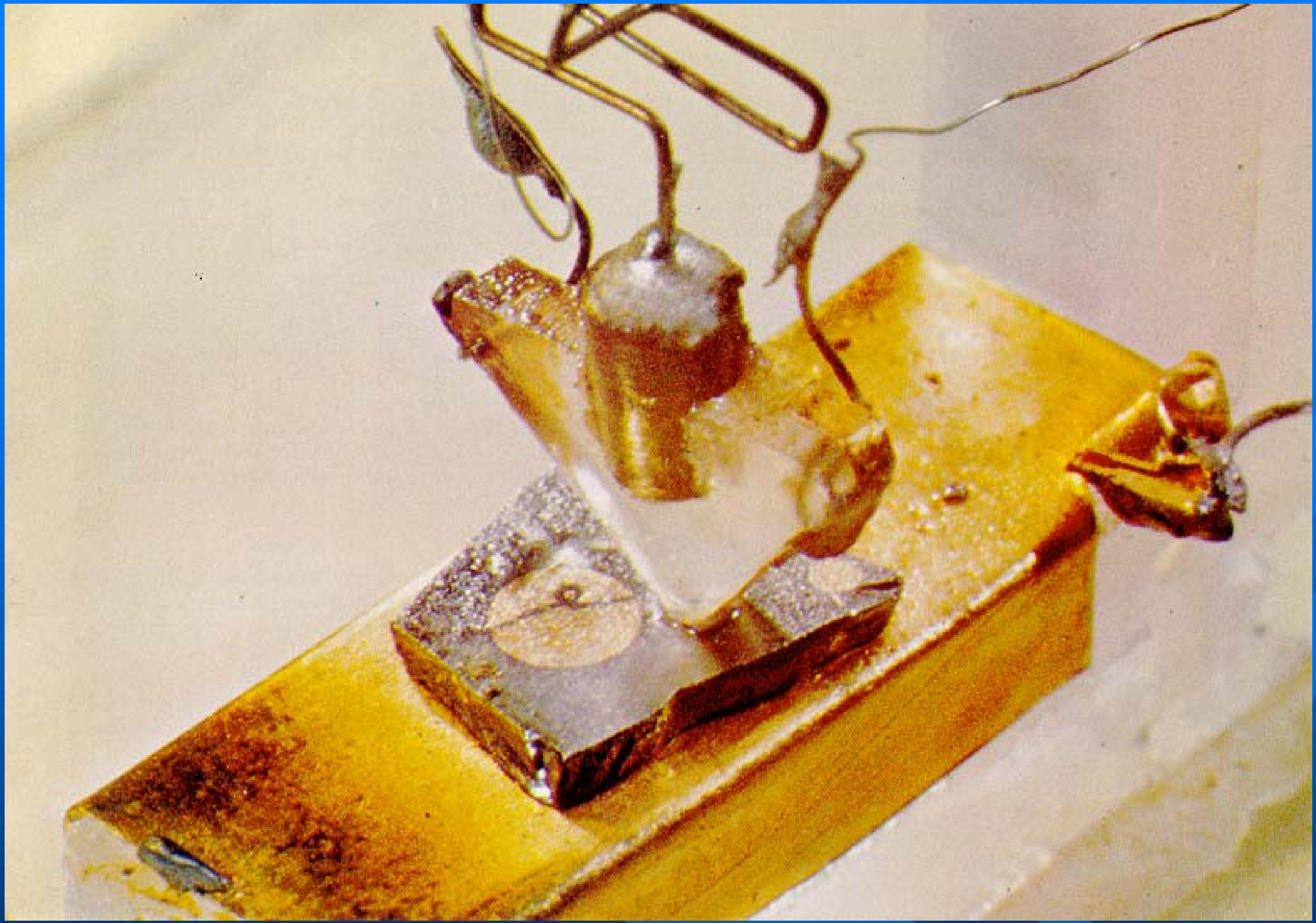
scope presentation appears as in Fig. 10·12 at (a). The sloping portion of the curve breaks away gradually from the nonconducting region and the slope of the curve increases with increasing forward voltage. Tapping lightly a few times produces the curve shown in Fig. 10·2 at (b). The break in the curve is more sharply defined and the curve takes on a constant slope with increased voltage. At this stage further tapping has little effect on the characteristic. As a final step the set screw in the cartridge head is screwed in tightly.

The amount of tapping done in the adjusting of the contact is a matter of the operator's judgment and experience. In addition to the changes in the characteristic curve mentioned, tapping has been observed in some cases to decrease the noise temperature of the rectifier. The crystal group[2] at the University of Pennsylvania has conducted controlled experiments where tapping was simulated by taking the contact

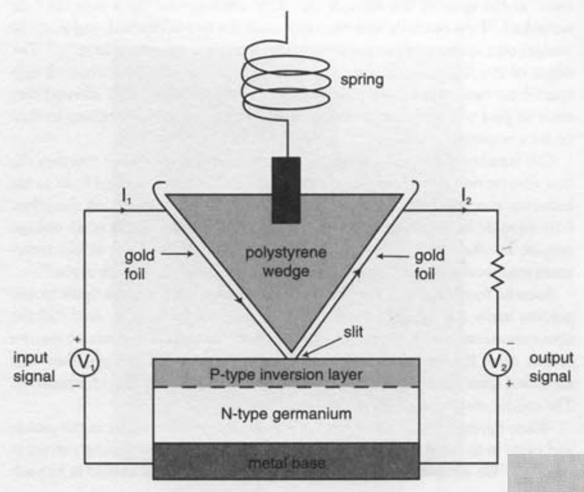
[1] "Tapping" means producing mechanical shock by blows of a light mallet.
[2] A. W. Lawson, P. H. Miller, L. I. Schiff, and W. E. Stephens, "Effect of Tapping on Barrier Capacitance," NDRC 14-181, Univ. of Penn., Sept. 1, 1943.

Discovery of the Transistor

- Controlling big power with little effort: amplification
- The Bell labs vision: Mervin J. Kelly
- Minority carrier injection and lifetime
- December 24, 1947
- The point contact transistor: shows the principle of amplification but is very fragile (J. Bardeen and W. Brattain)
- The junction transistor (W. Shockley)
- Are single crystals required?
- The generations of Ge and Si transistors: point contact Ge transistor → Ge junction transistor → alloyed Ge transistor → Ge mesa transistor (f_{max} = 500 MHz, Charles Lee, 1954) → Si planar transistor (Jean A. Hoerni, 1960)



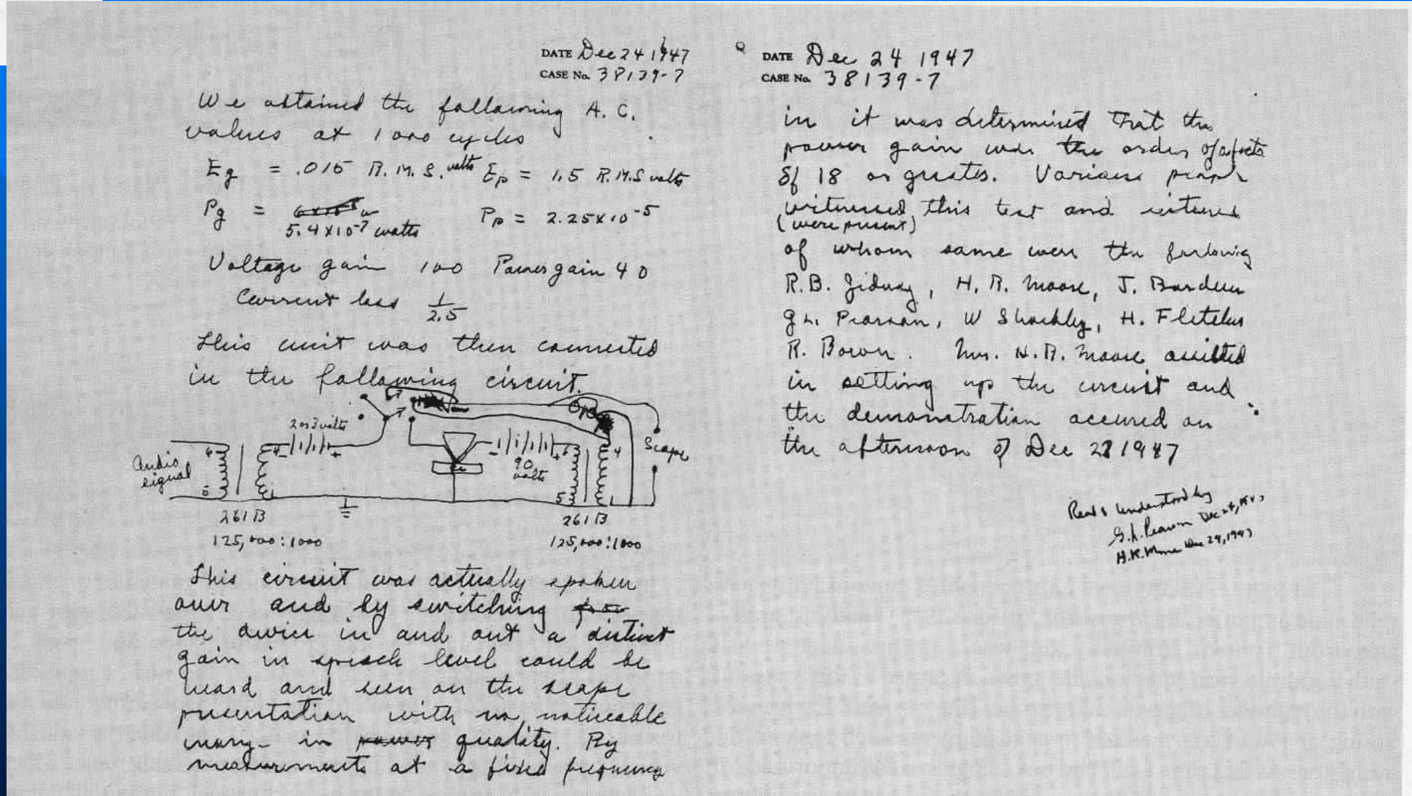
The first transistor fabricated by Bell Laboratories' scientists was this crude point-contact device, built with two cat's whiskers and a slab of polycrystalline germanium.



Cross-sectional diagram of the original point-contact semiconductor amplifier.

Point contact transistor schematic

The famous lab book entry of Christmas eve 1947:


DATE Dec 24 1947
CASE No. 38139-7

We obtained the following A.C. values at 1000 cycles.

E_g = .015 R.M.S. volts E_p = 1.5 R.M.S volts

P_g = 5.4×10^{-7} watts P_p = 2.25×10^{-5}

Voltage gain 100 Power gain 40

Current loss $\frac{1}{2.5}$

This unit was then connected in the following circuit.

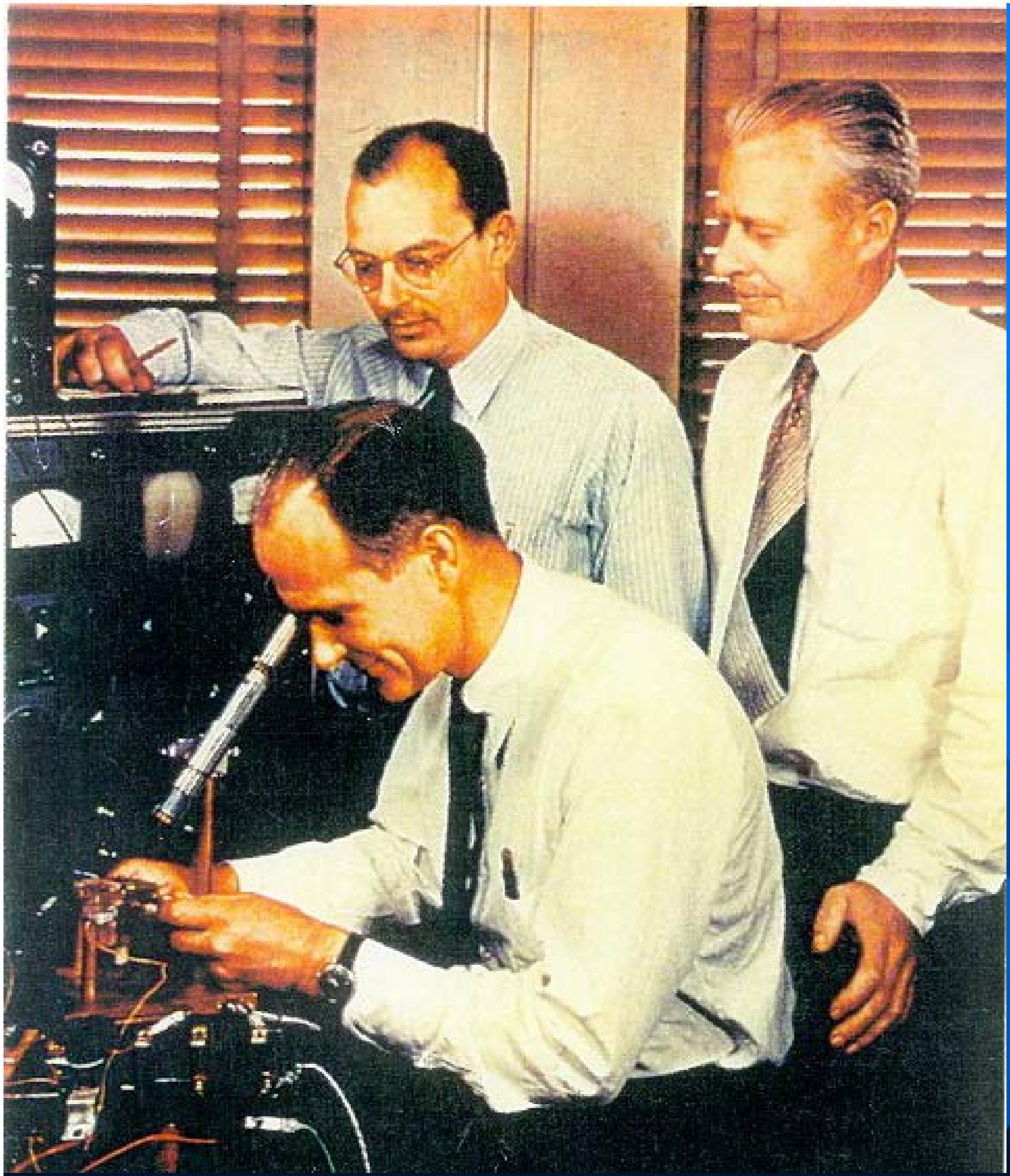
This circuit was actually spoken over and by switching ~~from~~ the device in and out a distinct gain in speech level could be heard and seen on the scope presentation with no noticeable change in ~~power~~ quality. By measurements at a fixed frequency

DATE Dec 24 1947
CASE No. 38139-7

in it was determined that the power gain was the order of a factor of 18 or greater. Various people witnessed this test and listened (were present) of whom some were the following R.B. Gibney, H.R. Moore, J. Bardeen, G.L. Pearson, W Shockley, H. Fletcher R. Bown. Mr. H.R. Moore assisted in setting up the circuit and the demonstration occurred on the afternoon of Dec 23 1947

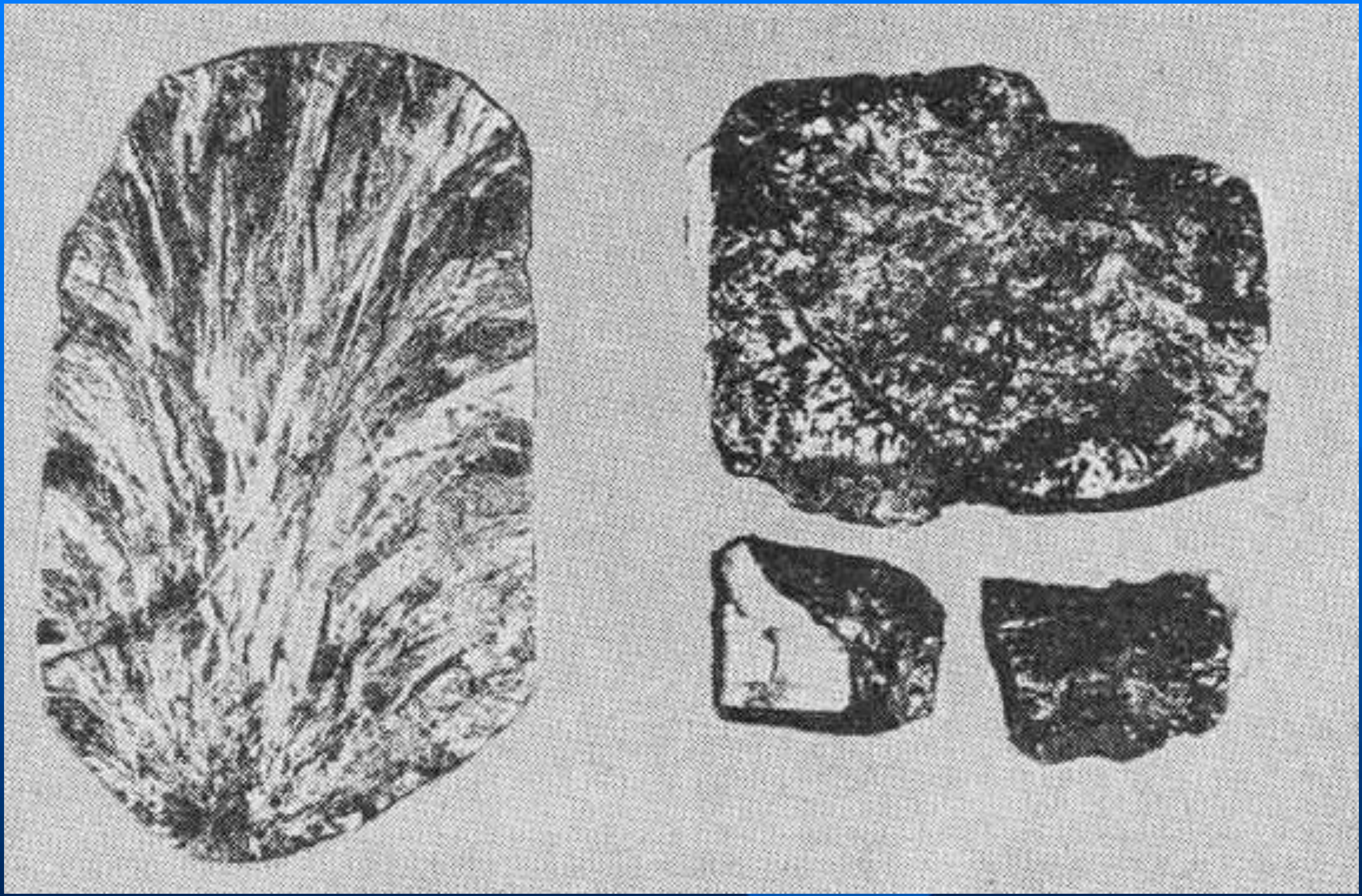
Read & understood by
G.L. Pearson Dec 24, 1947
H.R. Moore Dec 24, 1947

This laboratory notebook entry of Walter H. Brattain records the events of December 23, 1947 which was the date of the first demonstration of the point contact transistor used as a speech amplifier. H.R Moore assisted in setting up the demonstration, and he and G.L. Pearson signed Brattain's notebook entry as witnesses. Also present at the demonstration were R.B. Gibney, J. Bardeen, W. Shockley, H. Fletcher, and R. Bown.

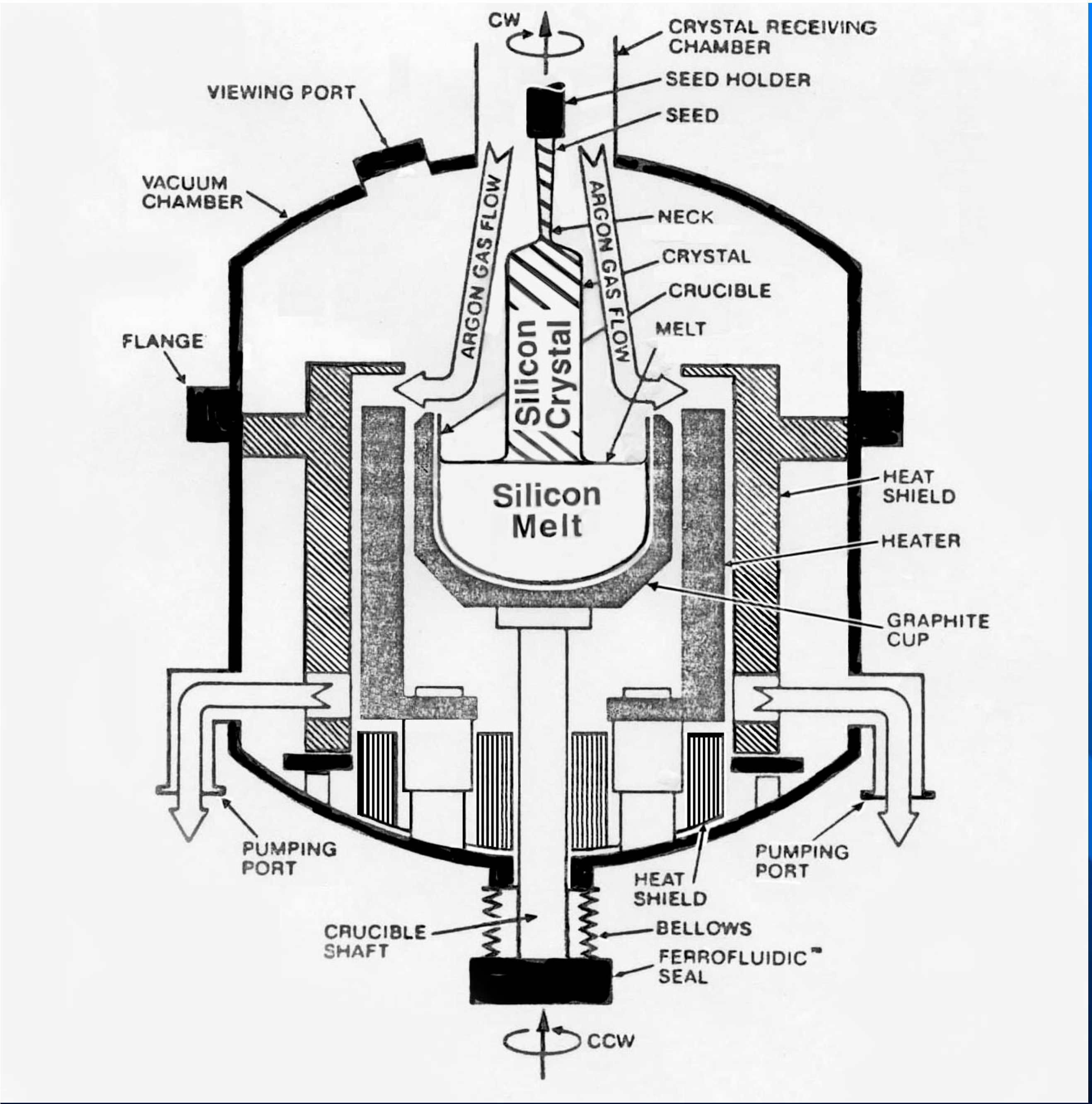


William Shockley, John Bardeen and Walter Brattain (left to right) are gathered together around an experiment in this historic 1948 photograph. The first point contact transistor remains on display at AT&T Bell Labs in Murray Hill, New Jersey.

Is Polycrystalline Material Reproducible?



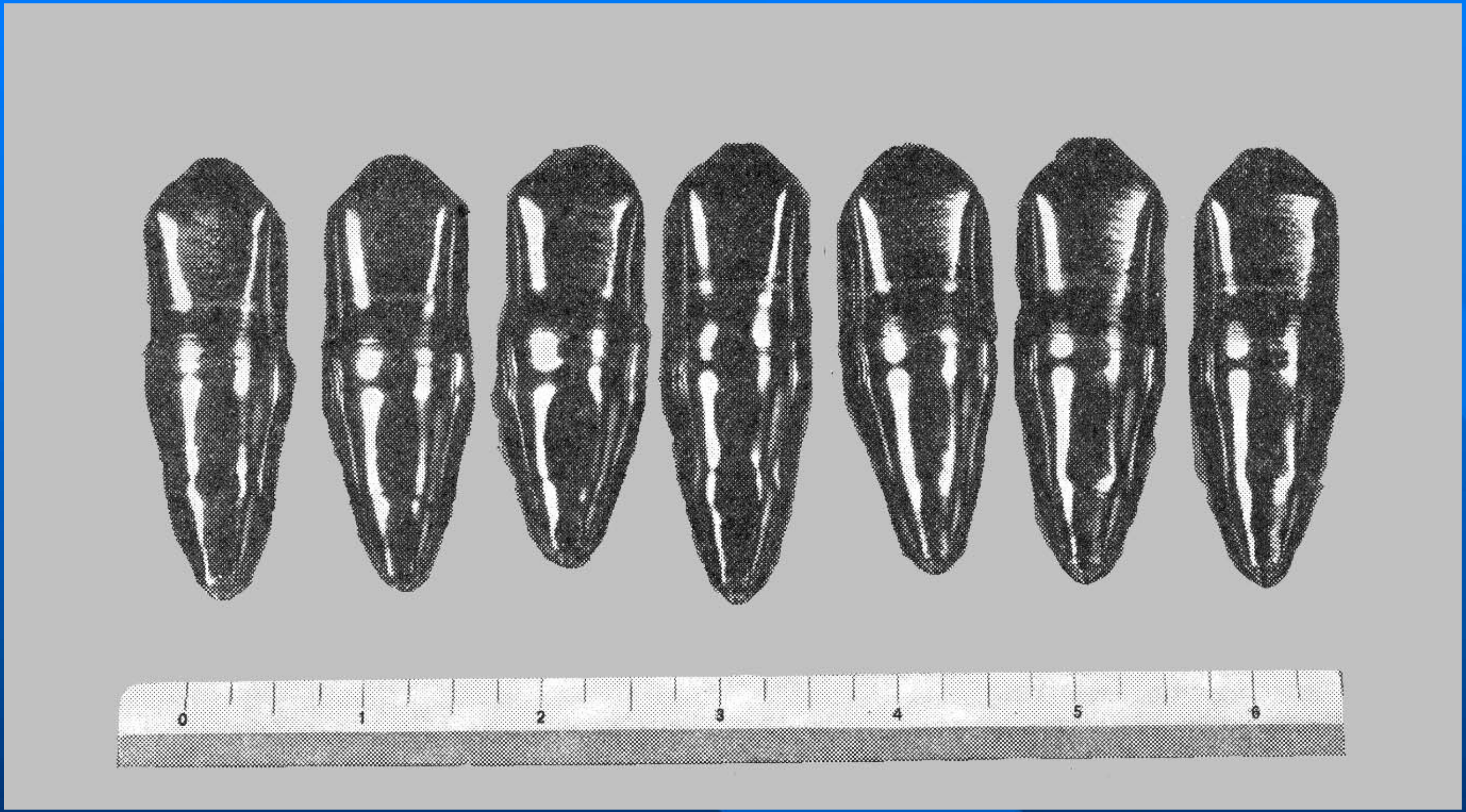
Variation in melting practice and its effect on the physical characteristics of the silicon ingot



Jan Czochralski

Sketch of a modern CZ-puller

Teal and Little's Hard Fought Victory*



Uniformity of crystal geometry obtainable with the pulling technique (i.e., the Czochralski technique).

*G.K. Teal and J.B. Little, Phys. Rev., **78** (1950) 647

The First Semiconductor Energy Band Structure

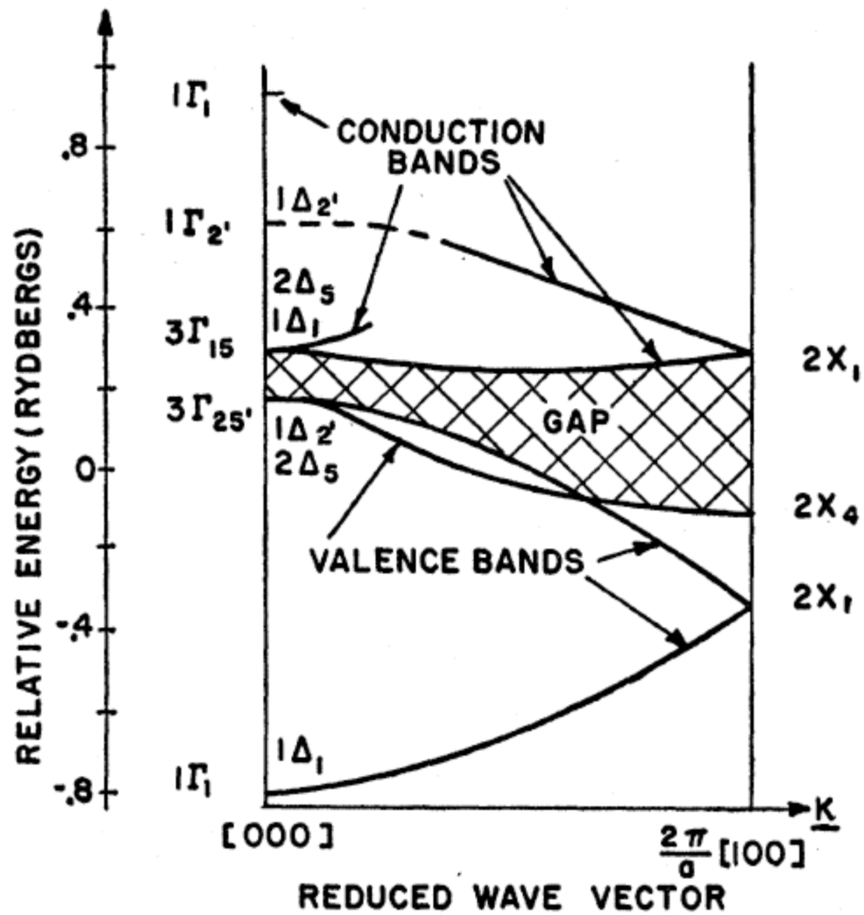


FIG. 1. Energy band structure of the germanium crystal. The present study was restricted to the points $\mathbf{k}=000$ and $k=2\pi(100)/a$. The curves joining the calculated eigenvalues indicate the estimated trends, based on the slopes and curvatures at the end points. The symbols denote degeneracy and symmetry classification. The notation is fully described in references 4 and 5.

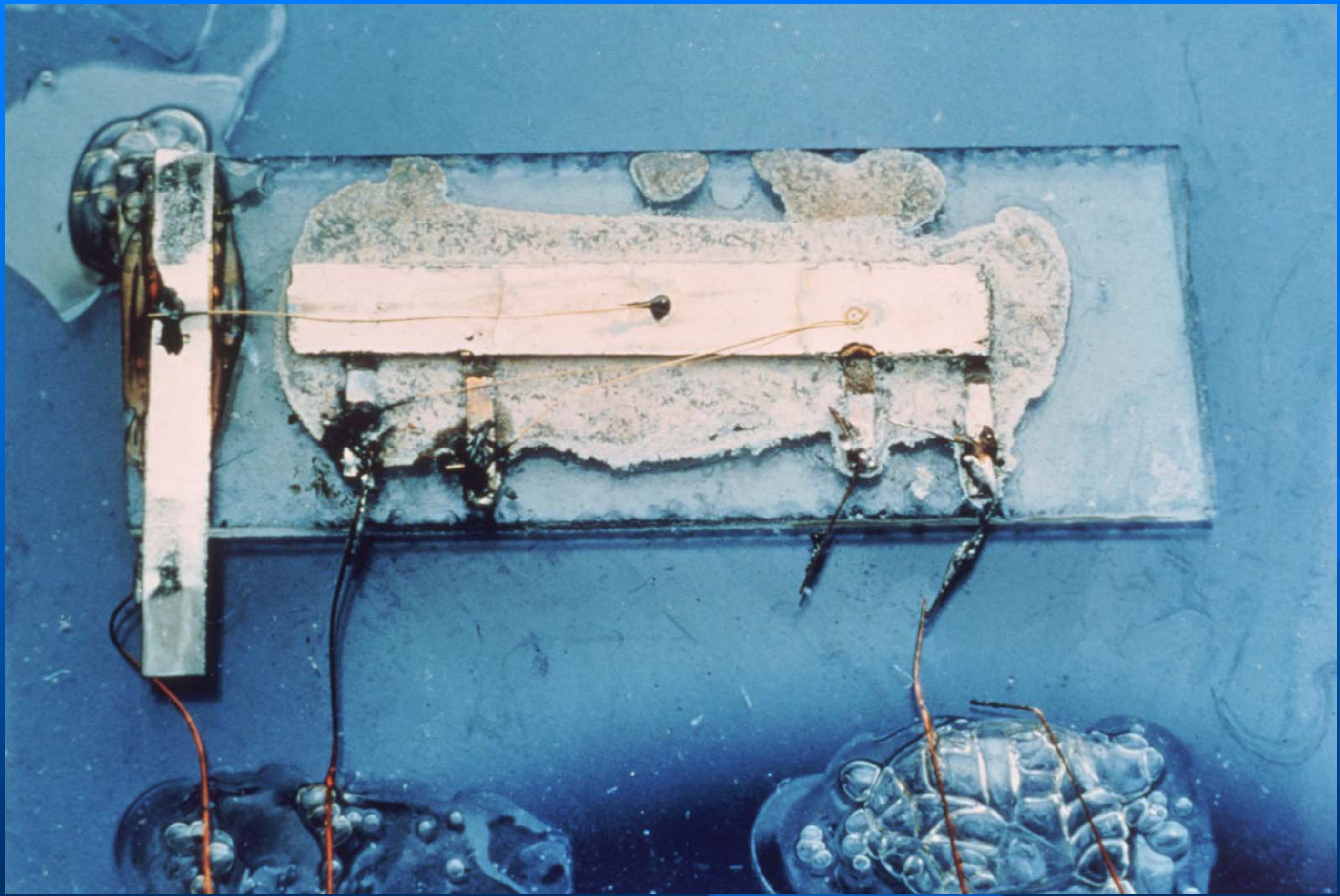
Electronic Structure of the Germanium Crystal

FRANK HERMAN AND JOSEPH CALLAWAY*
David Sarnoff Research Center, RCA Laboratories Division, Princeton, New Jersey

(Received November 25, 1952)

Physical Review **89**(2) 518-9 (1953)

The First Integrated Circuit



The first integrated germanium circuit built by J. Kilby at Texas Instruments in 1958.

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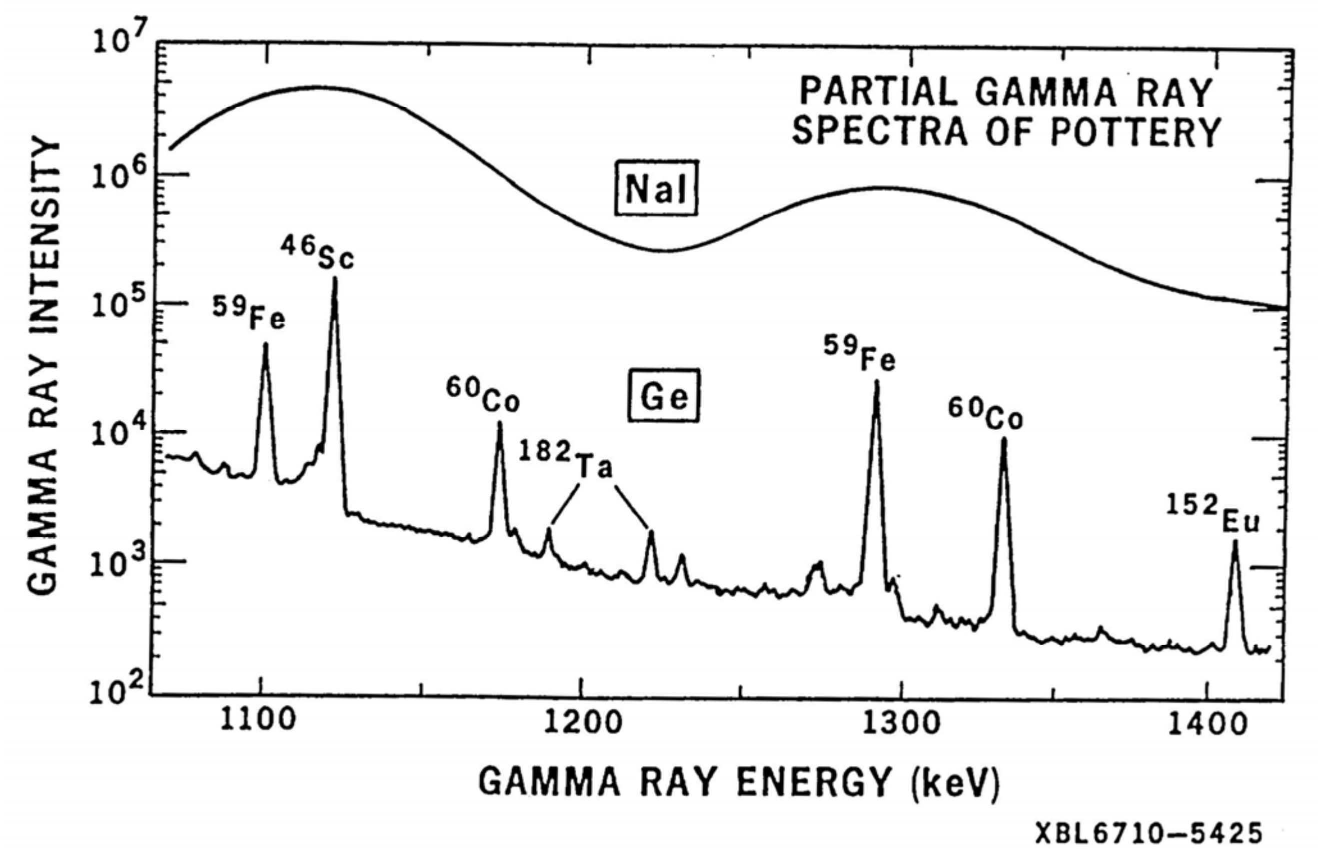
Applications of Germanium in Nuclear Physics: GeLi and hpGe Detectors



First Li drifted p-i-n Ge diode: D. V. Freck and J. Wakefield, Nature **193**, 669 (1962)

Ultra-Pure Ge: $N_A - N_D \leq 2x10^{10} cm^{-3}$

The Lawrence Berkeley Laboratory ultra-pure germanium growth apparatus. A water-cooled RF-powered coil surrounds the silica envelope of the puller. About half of the 25 cm long crystal has been grown.

The Berkeley High-Purity Ge Team

ERDA NEWS September 19, 1977

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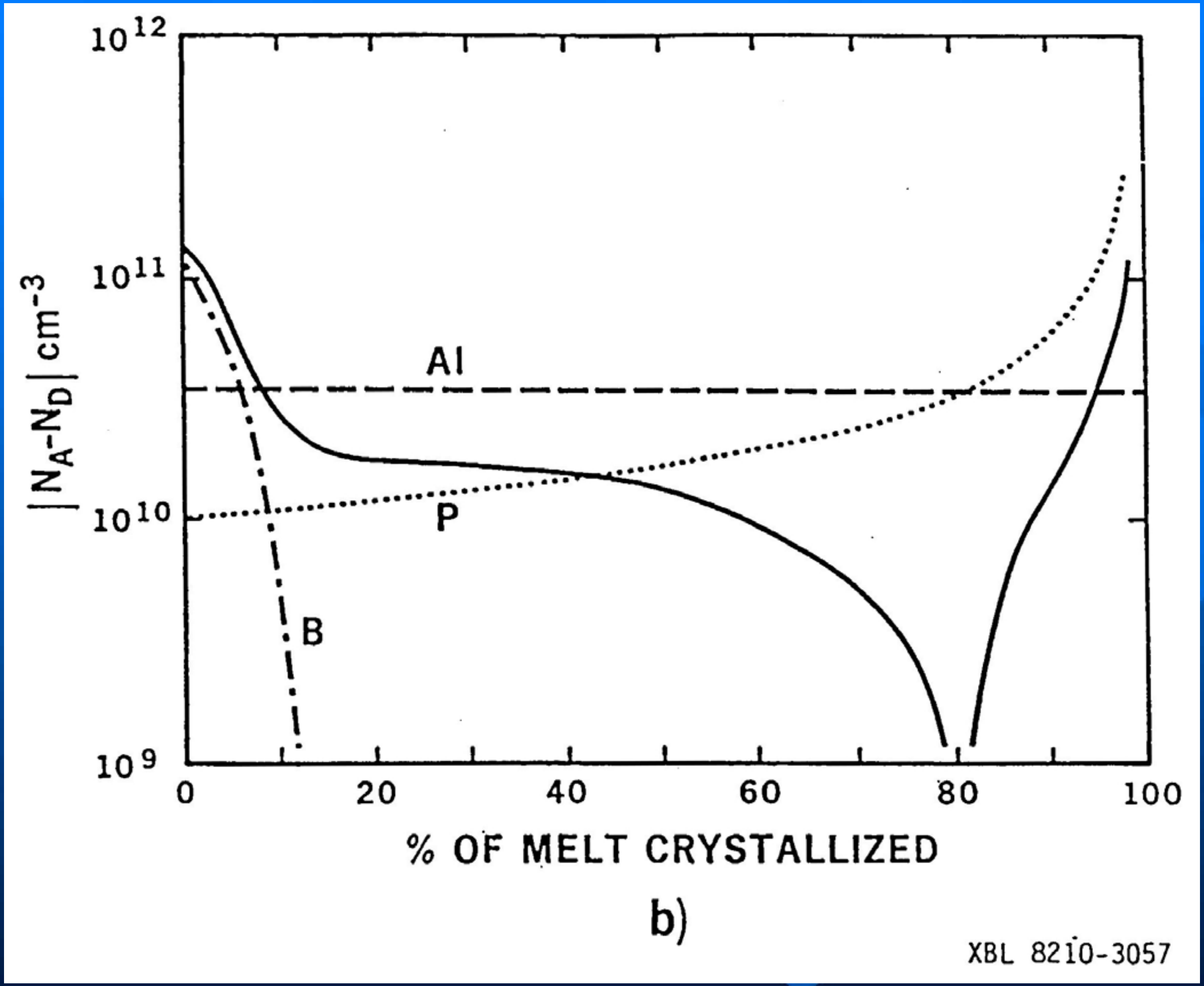
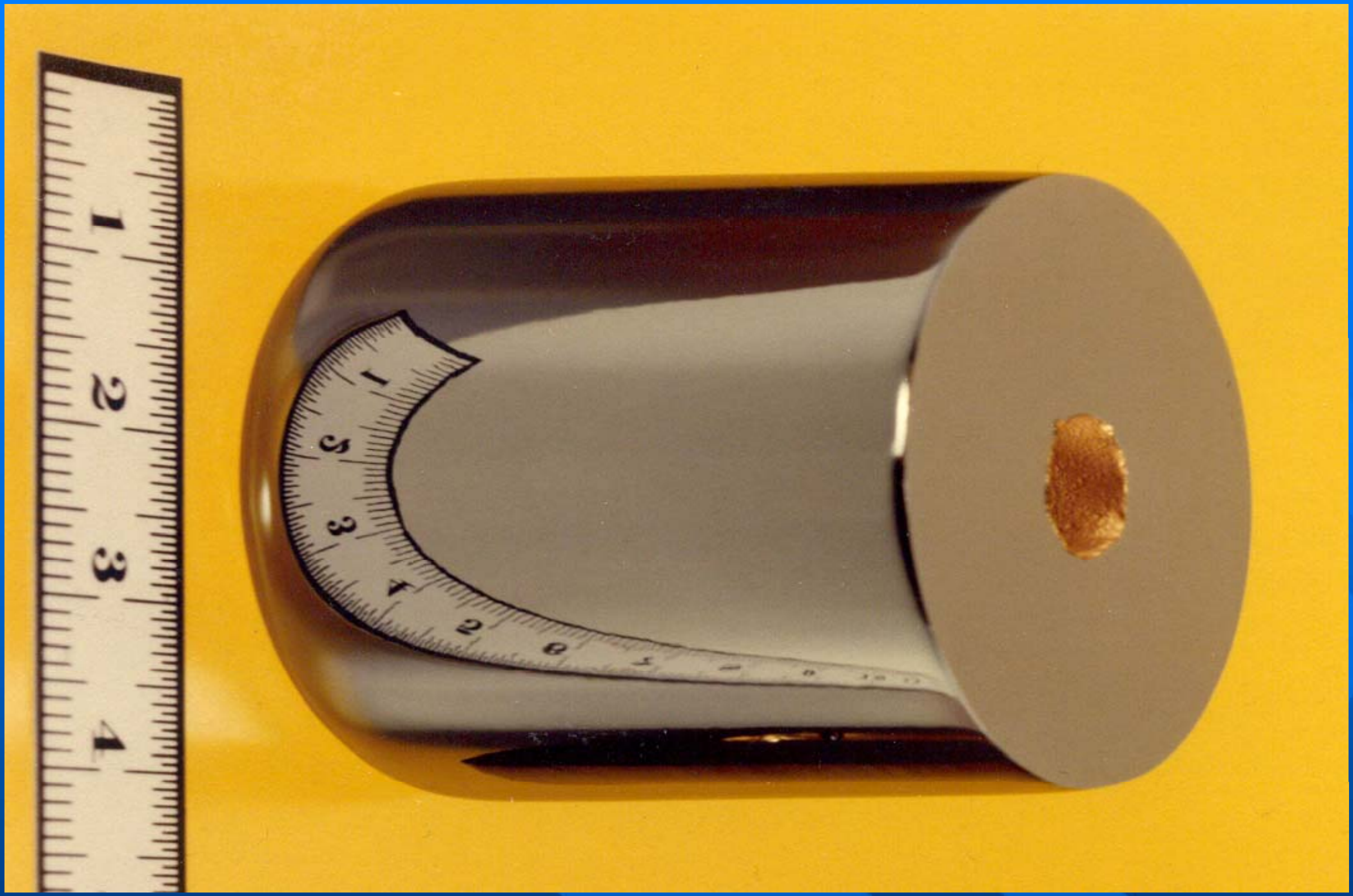
PURE AND COSTLY—Lawrence Berkeley Lab scientists (l-r) William Hansen, Eugene Haller and Scott Hubbard gaze at a germanium crystal worth about $15,000. Purified germanium has scientific applications in archeological dating, geological and chemical analysis, nuclear chemistry, physics and medicine. (LBL Photo)

Dopant Impurity Profiles



Impurity profiles in an ultra-pure Ge crystal with some boron (B, dot-dash line) segregating towards the seed end contaminates the crystal.



Ultra-pure germanium detector with closed-end coaxial contact geometry. The borehole reaches to within in ~ 2 cm of the backsurface of the p-i-n device and forms one contact. The whole outside surface except the flat portion surrounding the hole forms the other contact. Large volume detectors with small capacitance can be achieved with the coaxial geometry. (Courtesy of P.N. Luke, Lawrence Berkeley National Laboratory)

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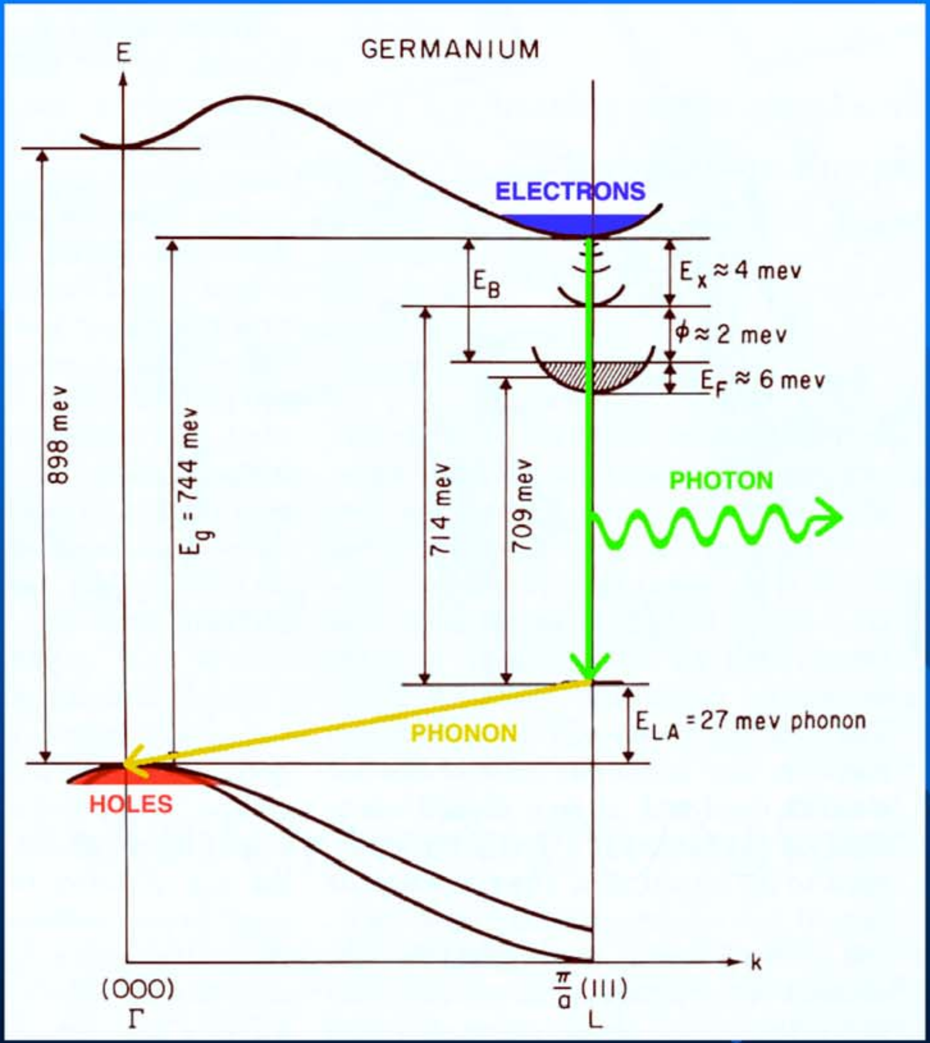
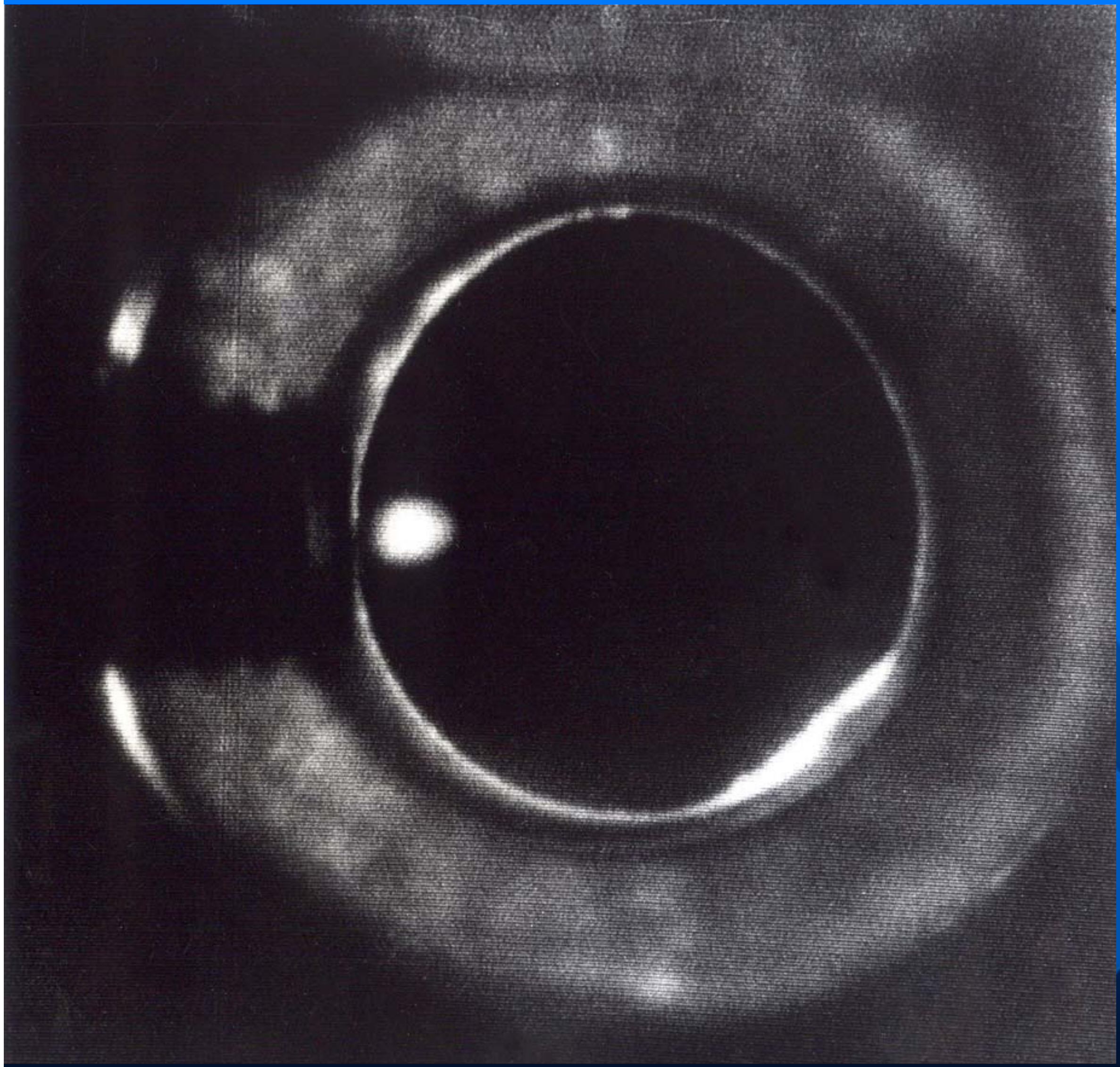
Physics with Ultra-Pure Germanium: Exciton Condensation



After C. D. Jeffries, Science **189**(4207), 955 (1971)

Electron-Hole Drops



Photograph of a long-lived electron-hole drop in a 4-mm disk of ultra-pure germanium. The sample is mounted in a dielectric sample holder and stressed by a 1.8-mm-diam screw discernible on the left.

See: J. P. Wolfe, W. L. Hansen, E. E. Haller, R. S. Markiewicz, C. Kittel, and C. D. Jeffries, Phys. Rev. Lett., **34** (1975) 1292.

Hydrogen Permeation Studies with Crystalline Germanium

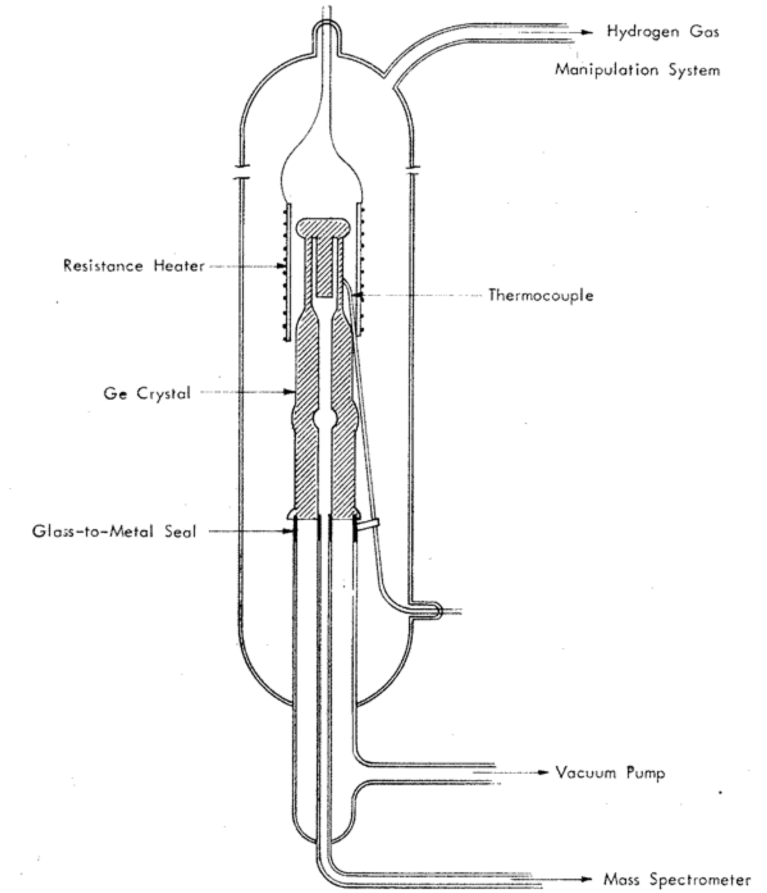


FIG. 2. Diagram of the gas chamber and crystal mounting.

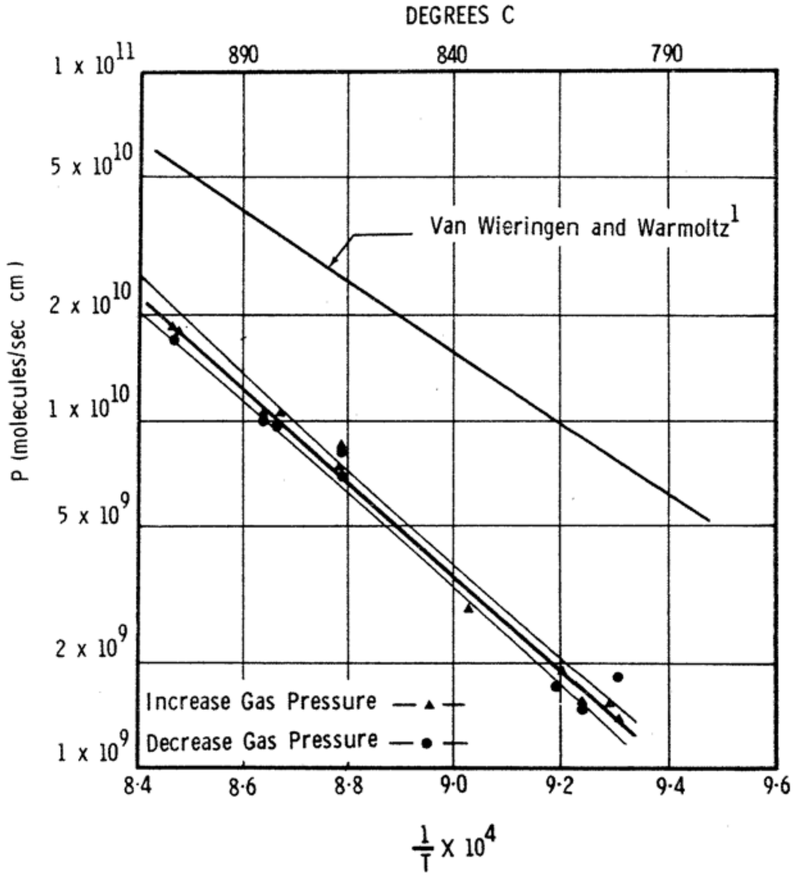
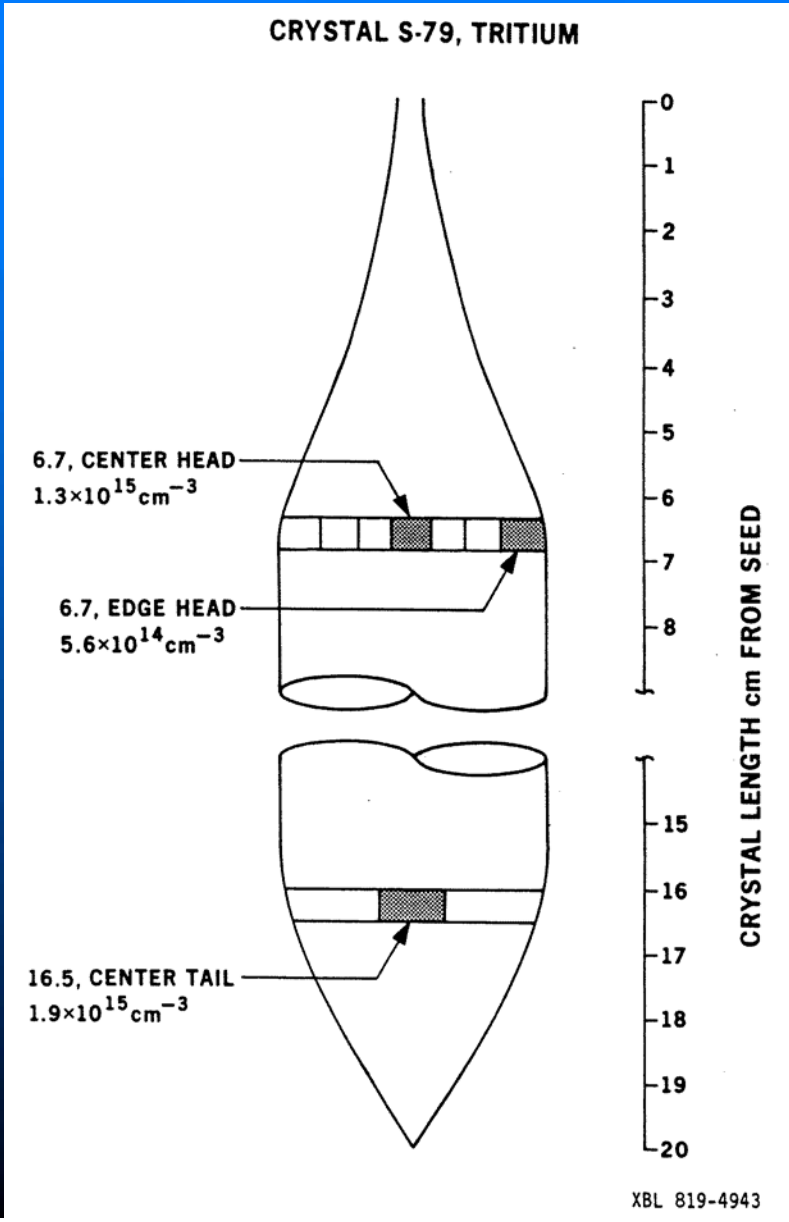


FIG. 4. Permeability, P, of hydrogen in germanium as a function of temperature.

Ref.: R.C. Frank and J.E. Thomas Jr., J. Phys. Chem. Solids **16**, 144 (1960)

Self-Counting Tritium Doped Ultra-Pure Ge Detector



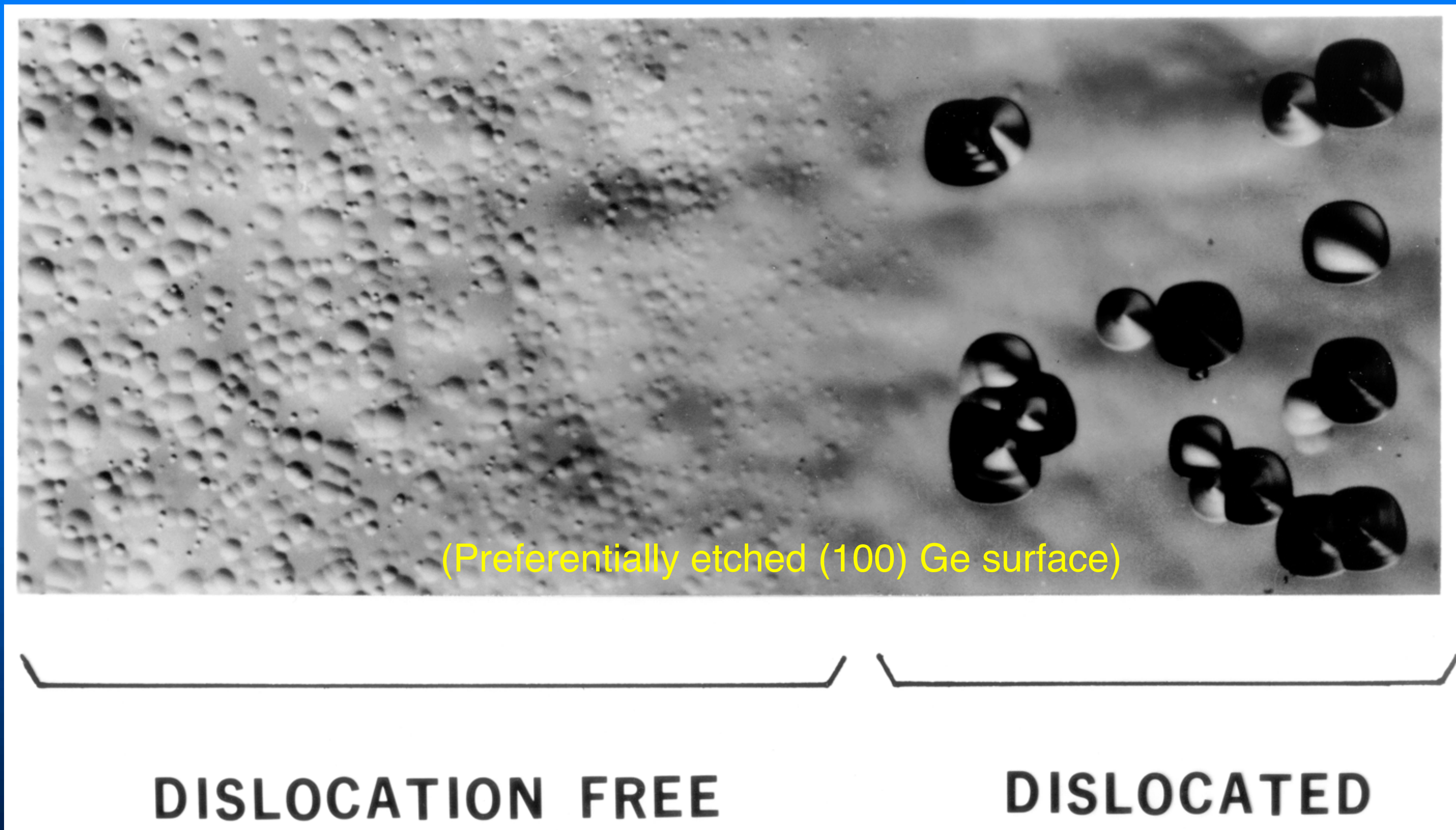
Tritium Labeling*:

$$ {}^{3}_{1}T \xrightarrow{\beta^-} {}^{3}_{2}He $$

Samples taken from *tritium-atmosphere-grown ultra-pure Ge crystal* at different locations were fashioned into radiation detectors, counting the internal T decays. The H concentration varies between $5x10^{14}$ and $2x10^{15}$ cm^{-3}.

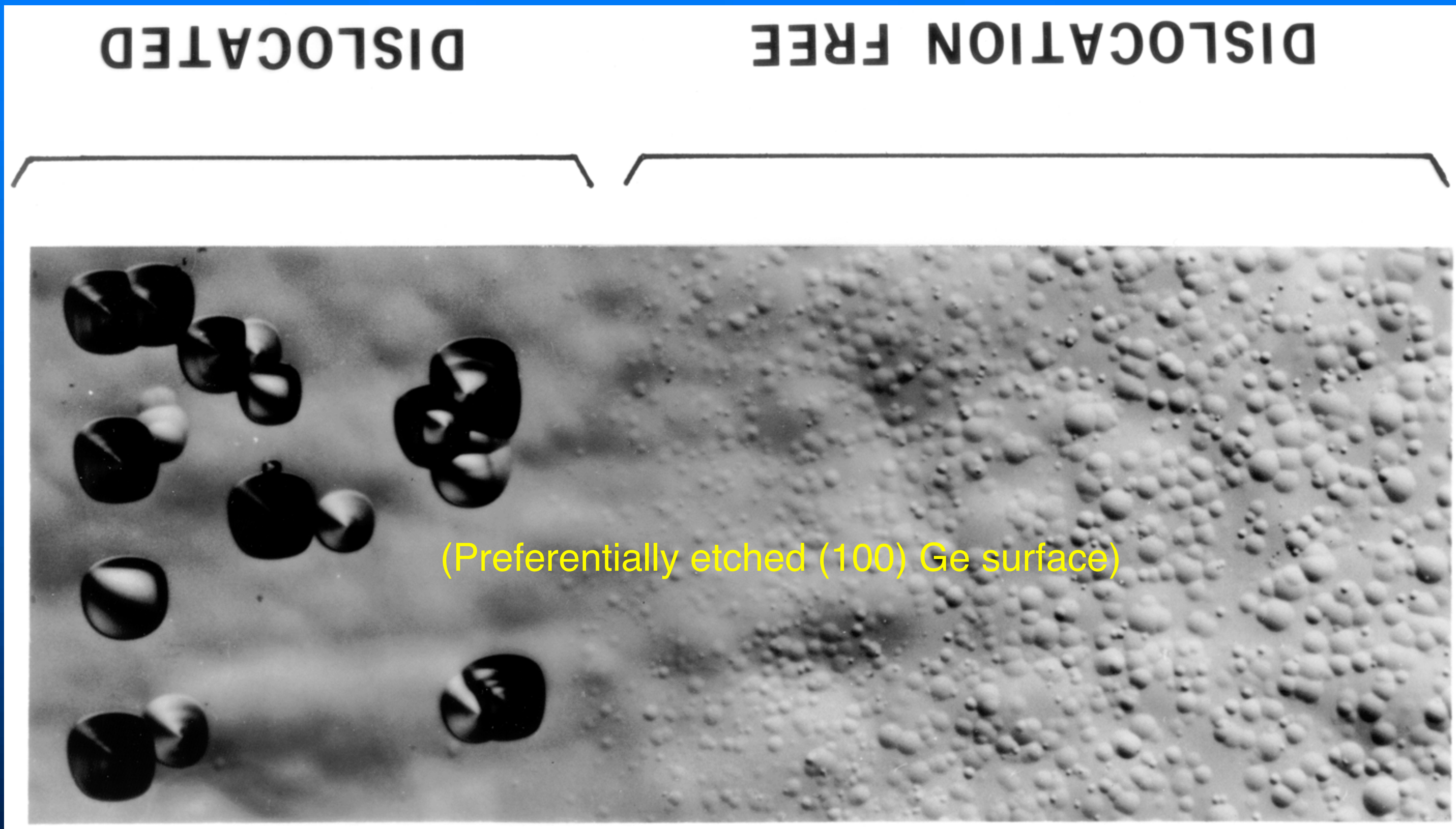
[*Ref.: W.L . Hansen, E.E. Haller and P.N. Luke, *IEEE Trans. Nucl. Sci.* **NS-29**, No. 1, 738 (1982)]

Hydrogen and Dislocations in Ge



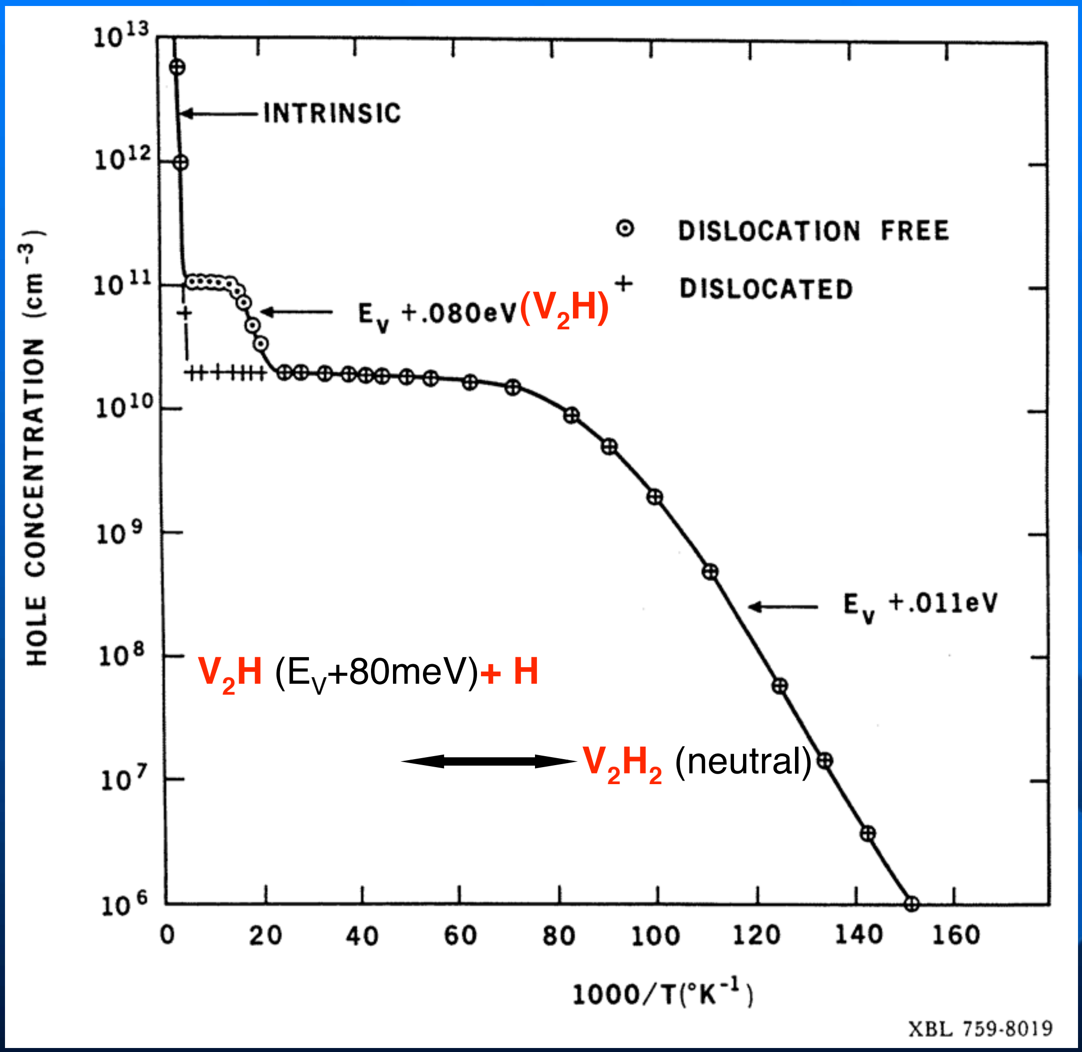
Ref.: E. E. Haller *et al.*, Inst. Phys. Conf. Ser. **31**, 309 (1977)

Hydrogen and Dislocations in Ge



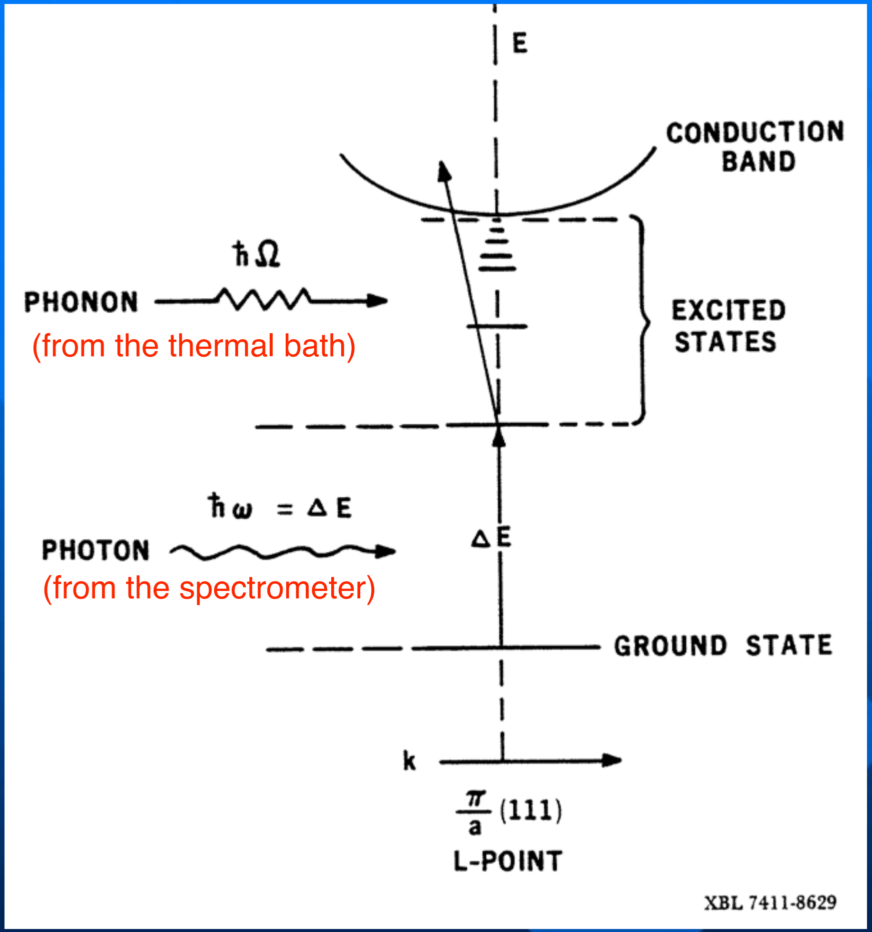
Ref.: E. E. Haller *et al.*, Inst. Phys. Conf. Ser. **31**, 309 (1977)

The V_2H Center in Dislocation Free, H_2 Atmosphere Grown Germanium

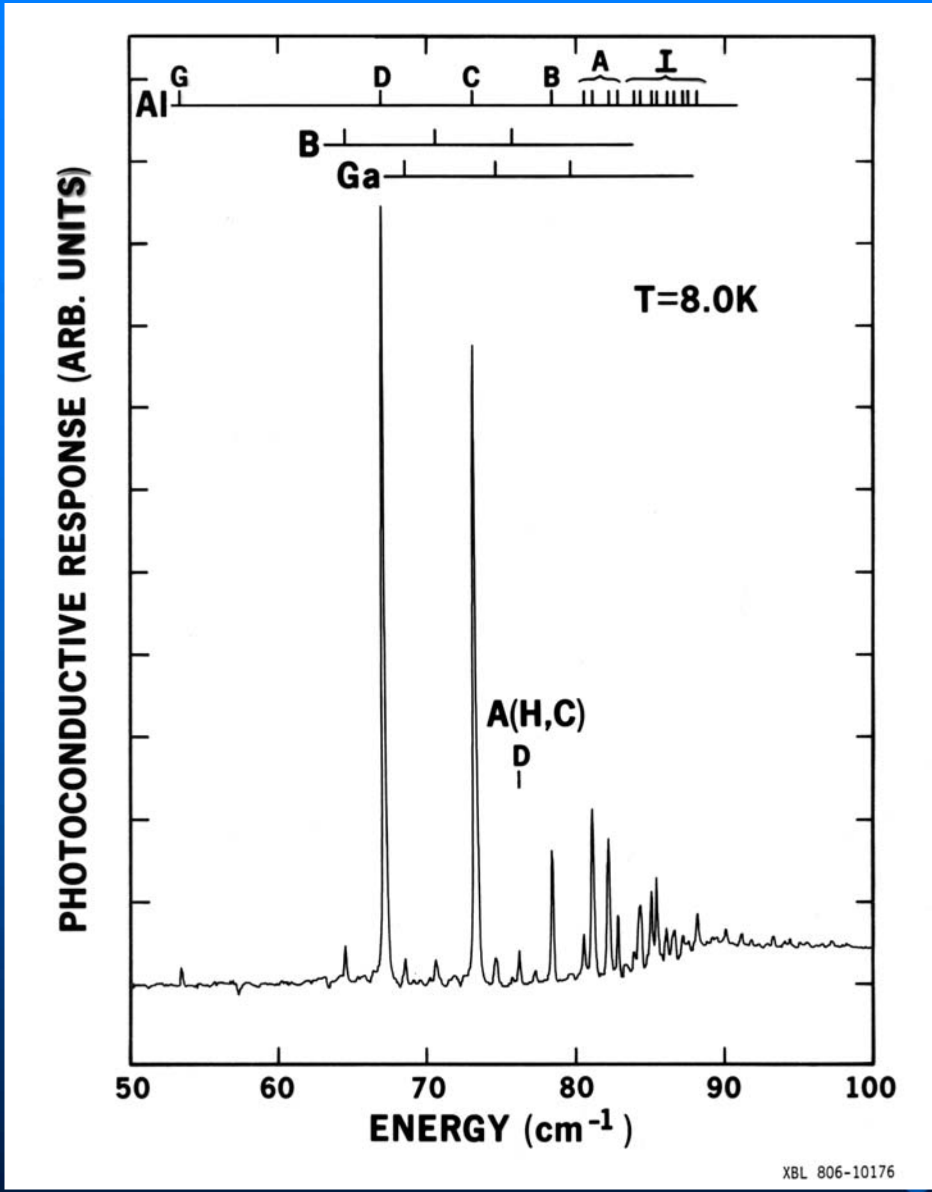


Log (hole concentration) against reciprocal temperature 1/T of a dislocated (+) and an undislocated (o) Ge sample cut from the same crystal slice. The net impurity concentration of shallow acceptors and donors is equal for both samples. The V_2H acceptor (E_v + 80 meV) only appears in the dislocation free piece (rich in vacancies); its concentration depends on the annealing temperature, [Ref.: E. E.Haller *et al.*, Proc. Intl. Conf. on Radiation Effects in Semiconductors 1976, N.B. Urli and J.W. Corbett, eds., *Inst. Phys. Conf. Ser.* **31**, 309 (1977)]

Photo Thermal Ionization Spectroscopy (PTIS)

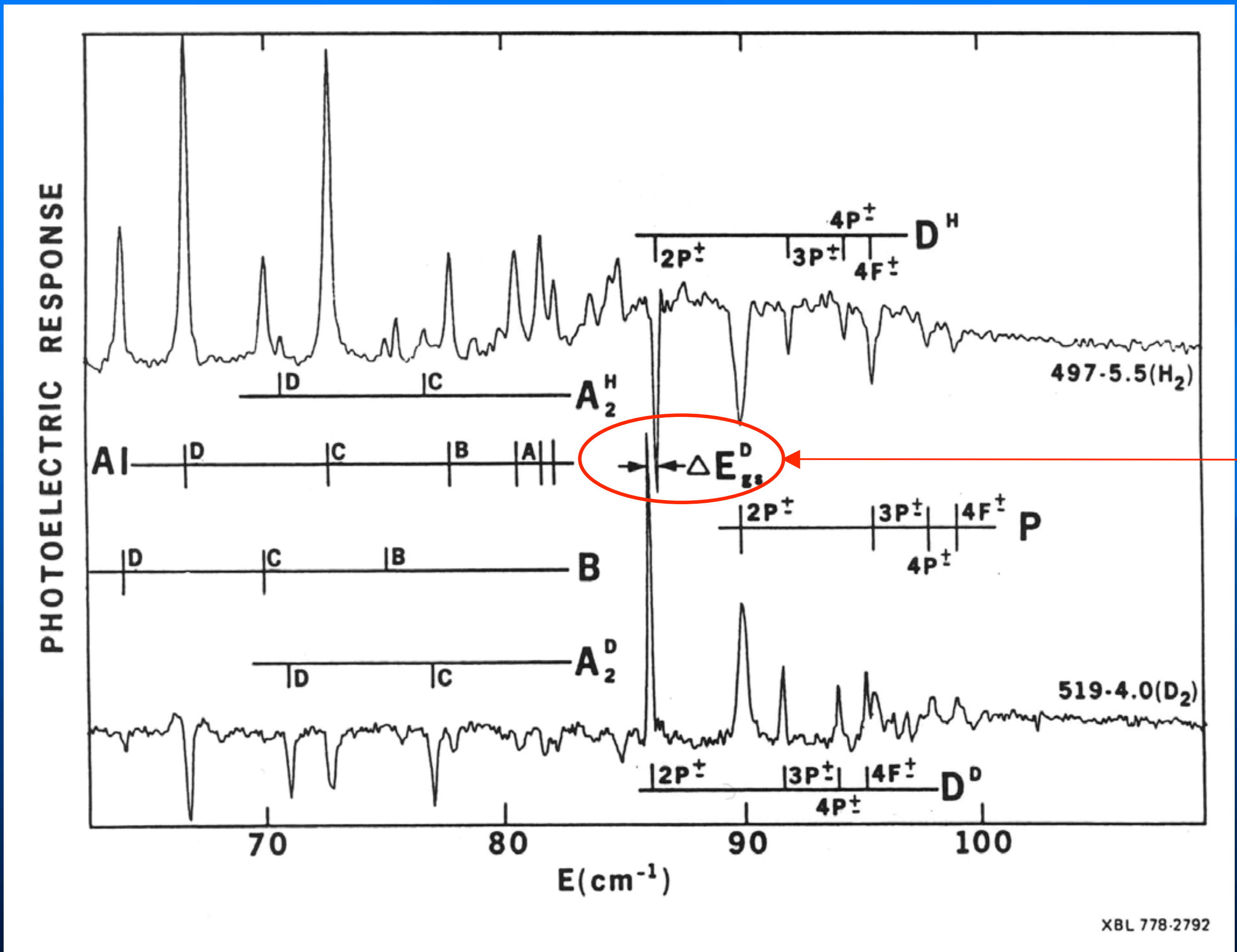


PTIS: Photo-Thermal Ionization Spectroscopy allows the study of extremely low dopant concentration [as low as 1 acceptor (donor) in 10^{14} host atoms]



Typical PTI Spectrum of ultra-pure germanium. The 5×5×5 mm^3 piece of the crystal had two ion implanted contacts on opposite faces. The net-acceptor concentration is 2×10^{10} cm^{-3}. Because of the high resolution, the small lines of B and Ga can be seen clearly.

Discovery of an Isotope Shift in the Ground State of the *Oxygen-Hydrogen Donor* and the *Silicon-Hydrogen* Acceptor in Germanium



pure H_2

51 μeV isotope shift!

pure D_2

Ref.: E.E. Haller, Phys. Rev. Lett. **40**, 584 (1978)

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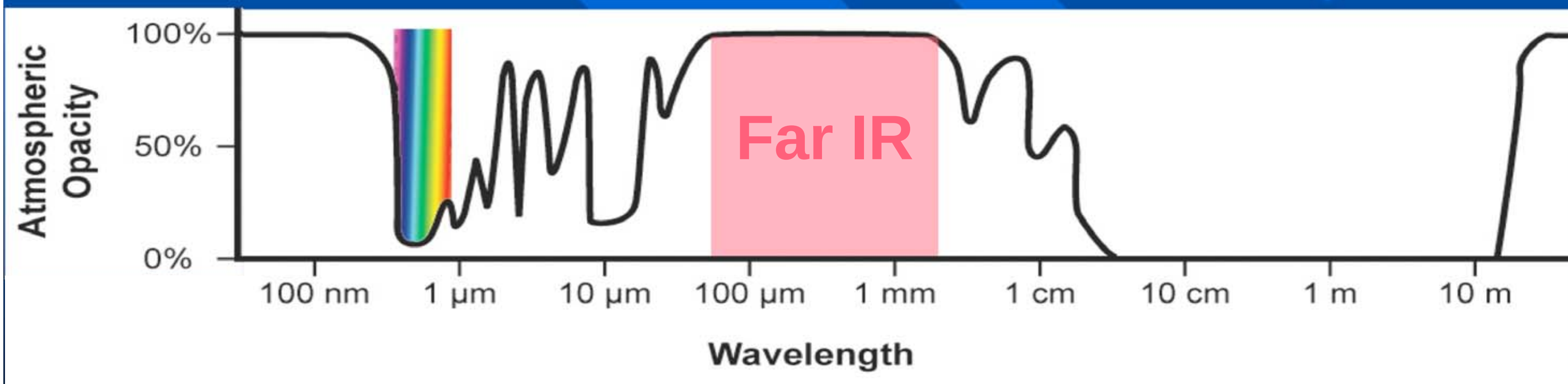
Extrinsic Ge Photoconductors for Far Infrared Astronomy

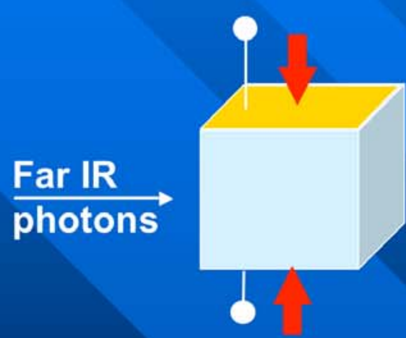
Interest: the far IR spectral range (50 to 2000 μm) contains information of great interest for the chemical composition of the Universe (vibrational and rotational molecular bands), for galaxy, star and planet formation and evolution, for views through cold and warm dust



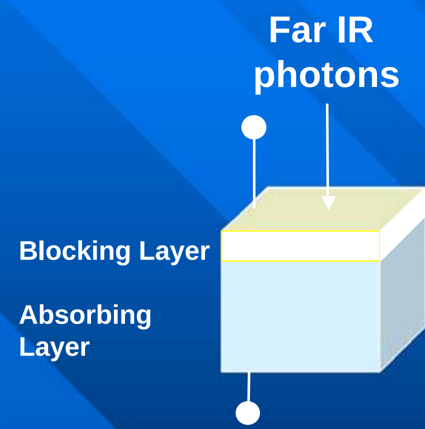
Extrinsic Ge Photoconductors

- Shallow dopants in Germanium have ionization energies near 10 meV (corresponding to 80 cm^{-1} or 125 µm). The low temperature photoconductive onset at $\lambda_{max} \cong 125$ µm lies in the far IR.
- Three generations of photoconductors:

Ge:Ga photo-conductor ($5x5x5mm^3$, $\lambda_{max} \cong 125$µm)
before 2000

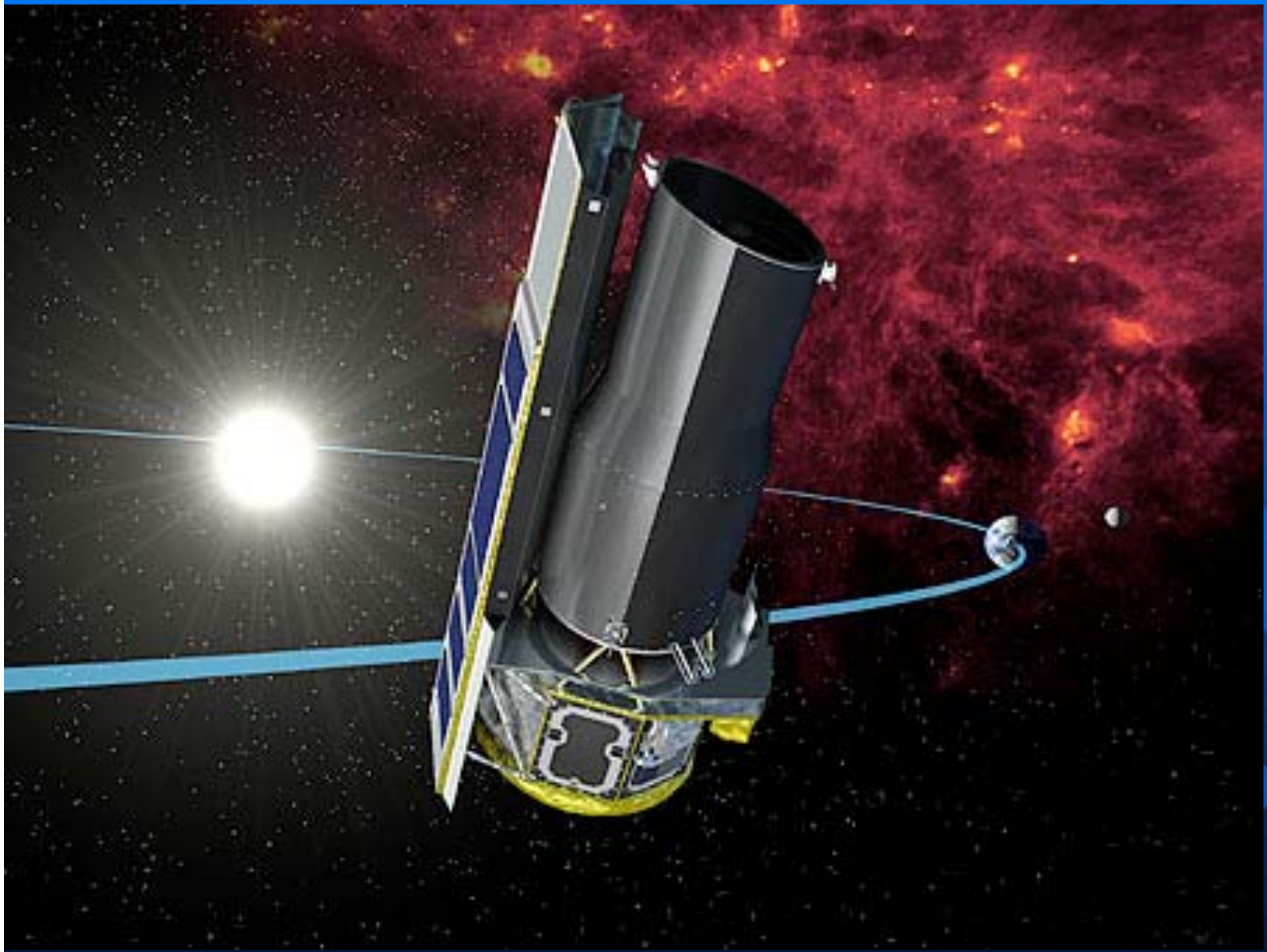


Stressed Ge:Ga photoconductor ($5x5x5mm^3$, $\lambda_{max} \cong 230$µm)
current



Ge:Ga Blocked Impurity Band detector ($\lambda_{max} > 250$µm)
after 2007

The Spitzer Space Telescope



- Launched in August 2003 on a two stage Delta rocket with 9 solid fuel boosters

- The liquid He cooled 0.85 m telescope is on an earth orbit vis-à-vis the earth

- wavelength range 3µm < l < 180µm

- Lifetime : up to 5 years

Observations with Ge Photoconductors

From visible light to the far infrared.

Galaxy Messier 81 at a distance of 12 Million light years!

Neutron Transmutation Doped (NTD) Germanium

- Irradiation of Ge with thermal neutrons
- Neutron captures and decays:

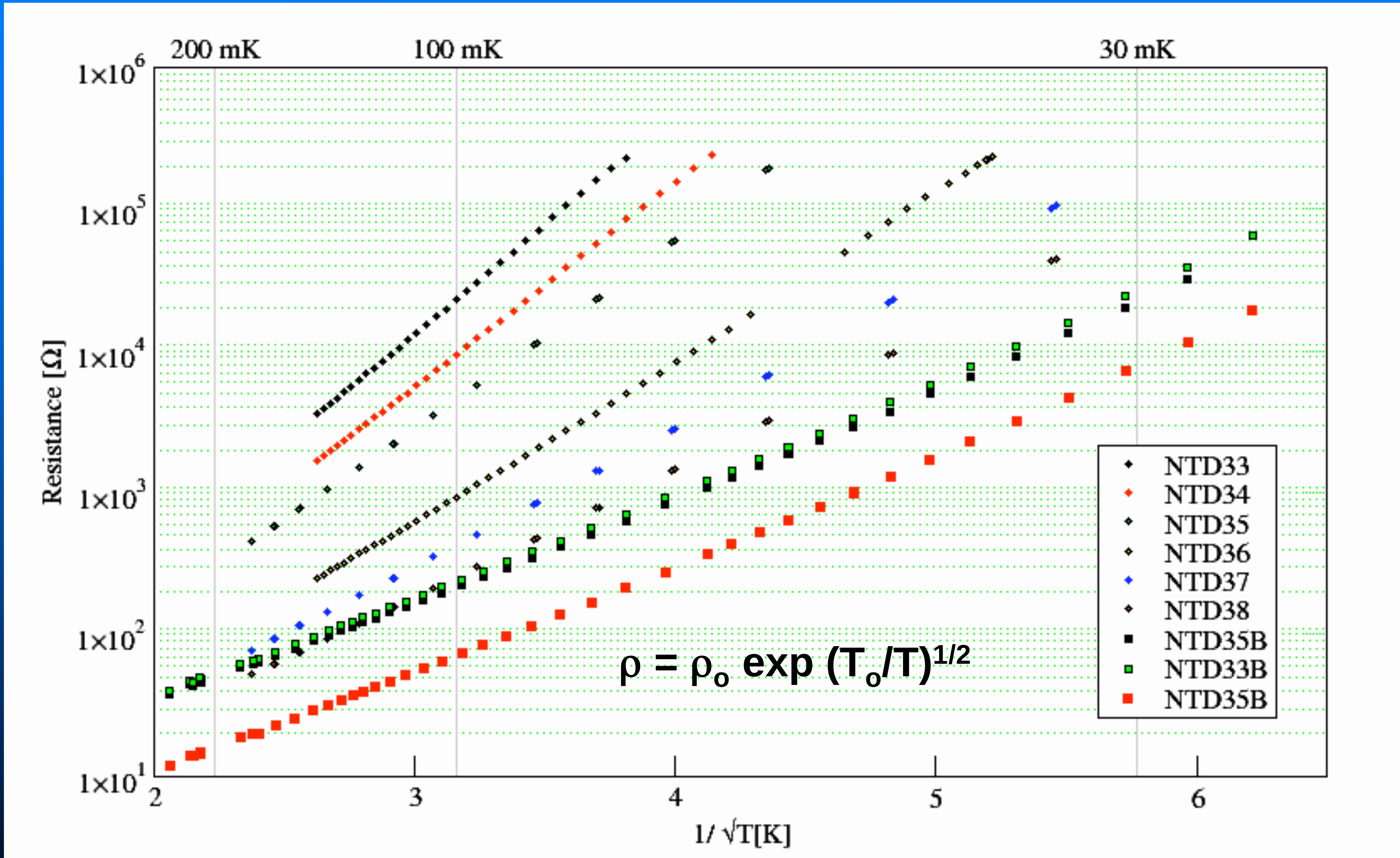
$$^{70}_{32}Ge(n,\gamma)^{71}_{32}Ge \xrightarrow[11.2d]{EC} {}^{71}_{31}Ga \ (acceptor)$$

$$^{74}_{32}Ge(n,\gamma)^{75}_{32}Ge \xrightarrow[82.2m]{\beta^-} {}^{75}_{33}As \ (donor)$$

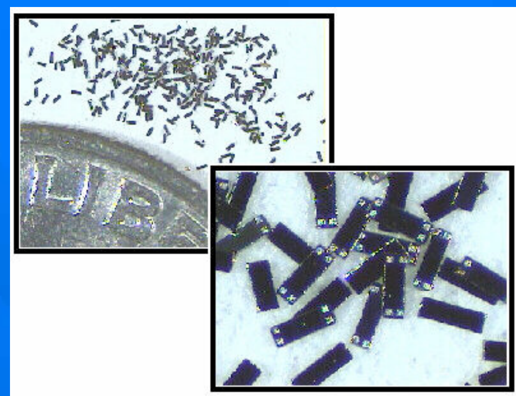
$$^{76}_{32}Ge(n,\gamma)^{77}_{32}Ge \xrightarrow[11.3h]{\beta^-} {}^{77}_{34}Se \ (double\ donor)$$

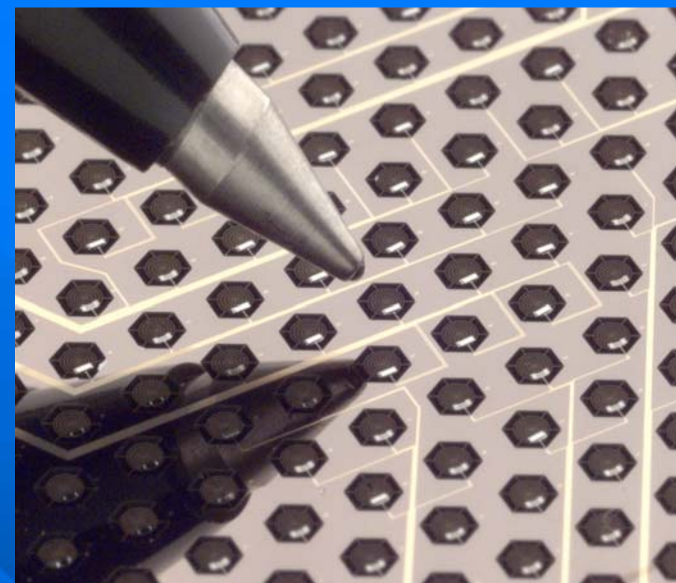
- Homogeneous impurity distribution reflects uniform neutron flux and uniform isotopic distribution
- Reproducibility: $N_{Ga} = \Phi\sigma_{^{70}Ge} N_{^{70}Ge}$
- Ultra-pure starting material
- Neutron doping levels >> residual impurities

R versus $T^{-1/2}$ for several NTD Ge Thermistors



Silicon Nitride Micromesh 'Spider-web' NTD Ge Bolometers





Spider-web architecture provides
- low absorber heat capacity
- minimal suspended mass
- low-cosmic ray cross-section
- low thermal conductivity = high sensitivity

Sensitivities and heat capacities achieved to date:
- NEP = 1.5 x 10-17 W/√Hz, C = 1pJ/K at 300 mK
- NEP = 1.5 x 10-18 W/ √ Hz, C = 0.4 pJ/K at 100mK

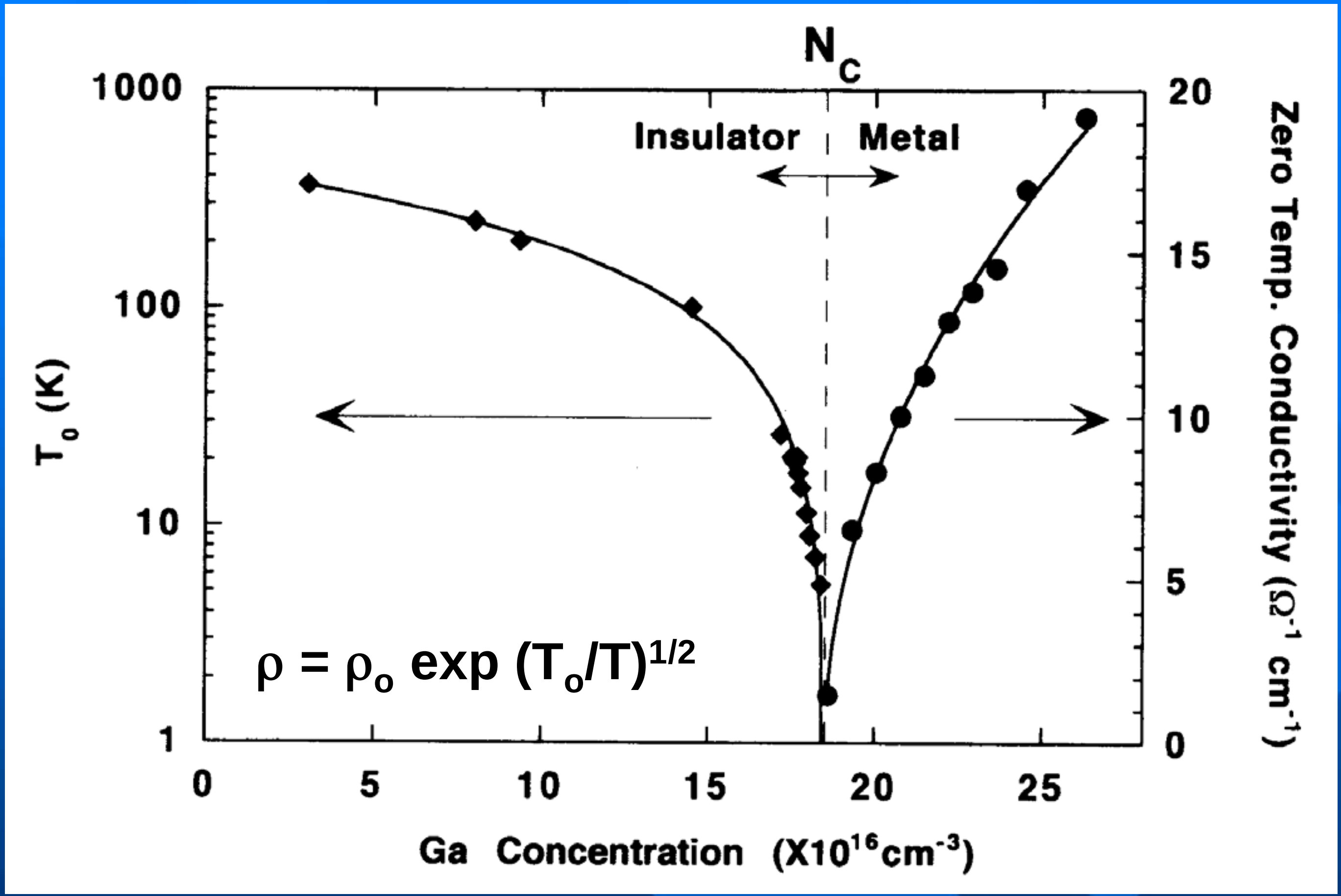
Detectors baselined for ESA/NASA Planck/HFI
Arrays baselined for ESA/NASA FIRST/SPIRE

Planned or operating in numerous sub-orbital experiments:

BOOMERANG	Caltech	Antarctic balloon CMB instrument
SuZIE	Stanford	S-Z instrument for the CSO
MAXIMA	UC Berkeley	North American balloon CMB instrument
BOLOCAM	CIT/CU/Cardiff	Bolometer camera for the CSO
ACBAR	UC Berkeley	Antarctic S-Z survey instrument
BICEP	Caltech	CMB polarimeter
Archeops	CNRS, France	CMB balloon experiment
BLAST	U. Penn	Submillimeter balloon experiment
Z-SPEC	Caltech	Mm-wave spectrometer
QUEST	Stanford	CMB polarimeter

Courtesy J. Bock, NASA-JPL

Metal-Insulator Transition with NTD ^{70}Ge



The left side shows the experimentally determined T_0 of 14 insulating samples as a function of Ga concentration (♦). The right side shows the zero temperature conductivity σ (0) obtained from the extrapolations σ (T) for ten metallic samples as a function of Ga concentration (•).

K. M. Itoh, *et al*., Phys. Rev. Lett. **77**(19), 4058-61 (1996).

Topics to be discussed

- Discovery of Germanium and Early History
- From the "Physics of Dirt" to a Respectable Science
- Point Contact Diodes and Transistors
- Applications of Germanium in Nuclear Physics: GeLi and High-Purity Ge detectors
- New Physics with Ultra-Pure Germanium
- Infrared Photoconductors and Bolometers
- Isotopically Controlled Germanium
- Germanium Speeds Up Silicon Transistors

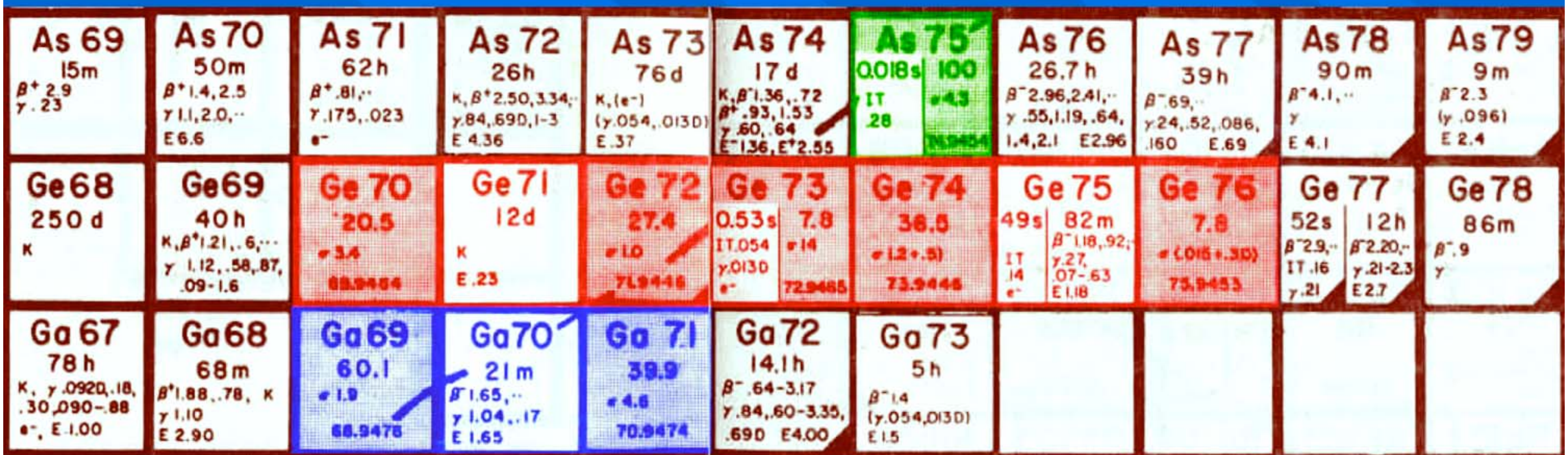
STABLE ISOTOPES

^{75}As

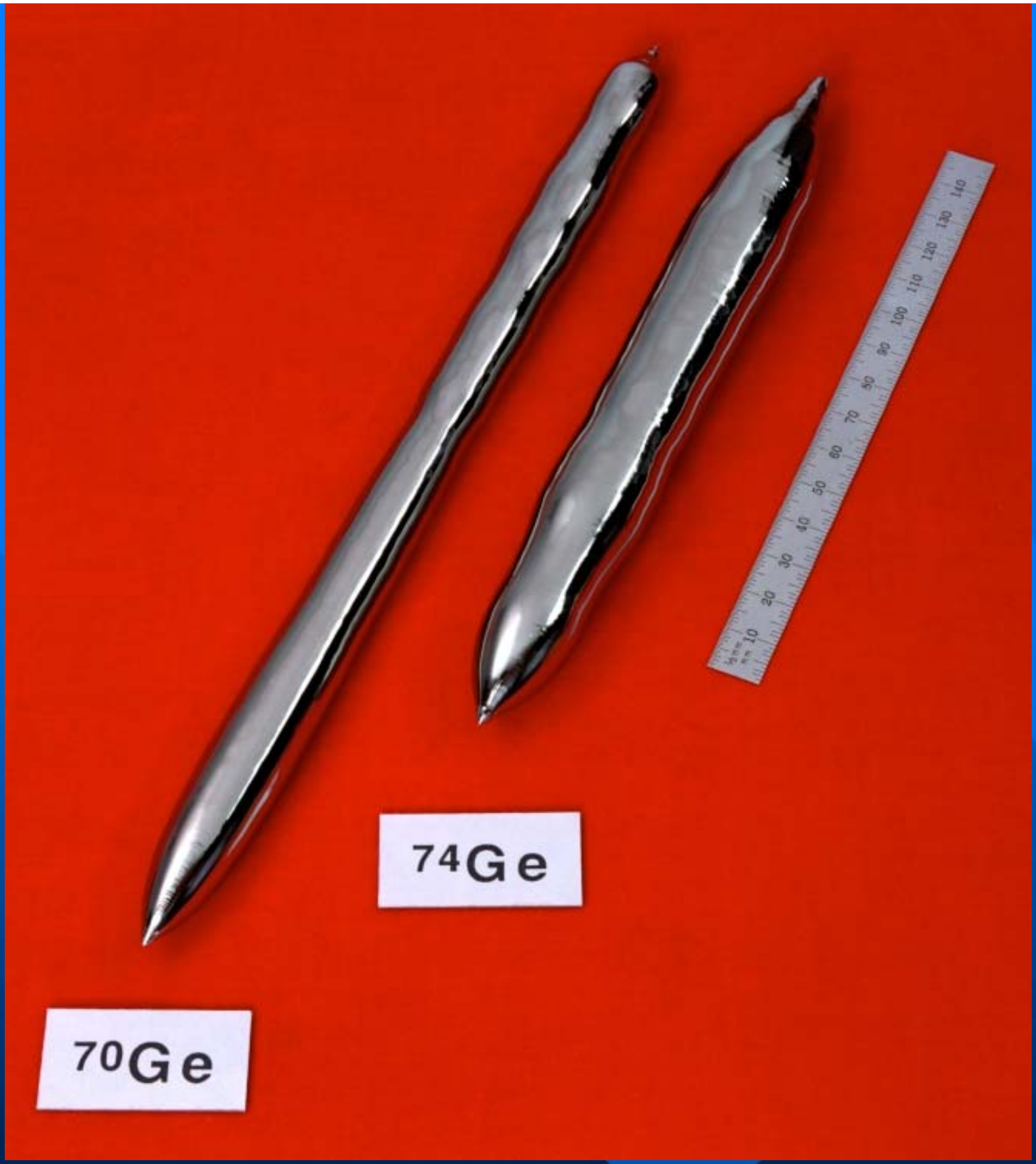
^{70}Ge, ^{72}Ge, ^{73}Ge, ^{74}Ge, ^{76}Ge

^{69}Ga, ^{71}Ga

Z

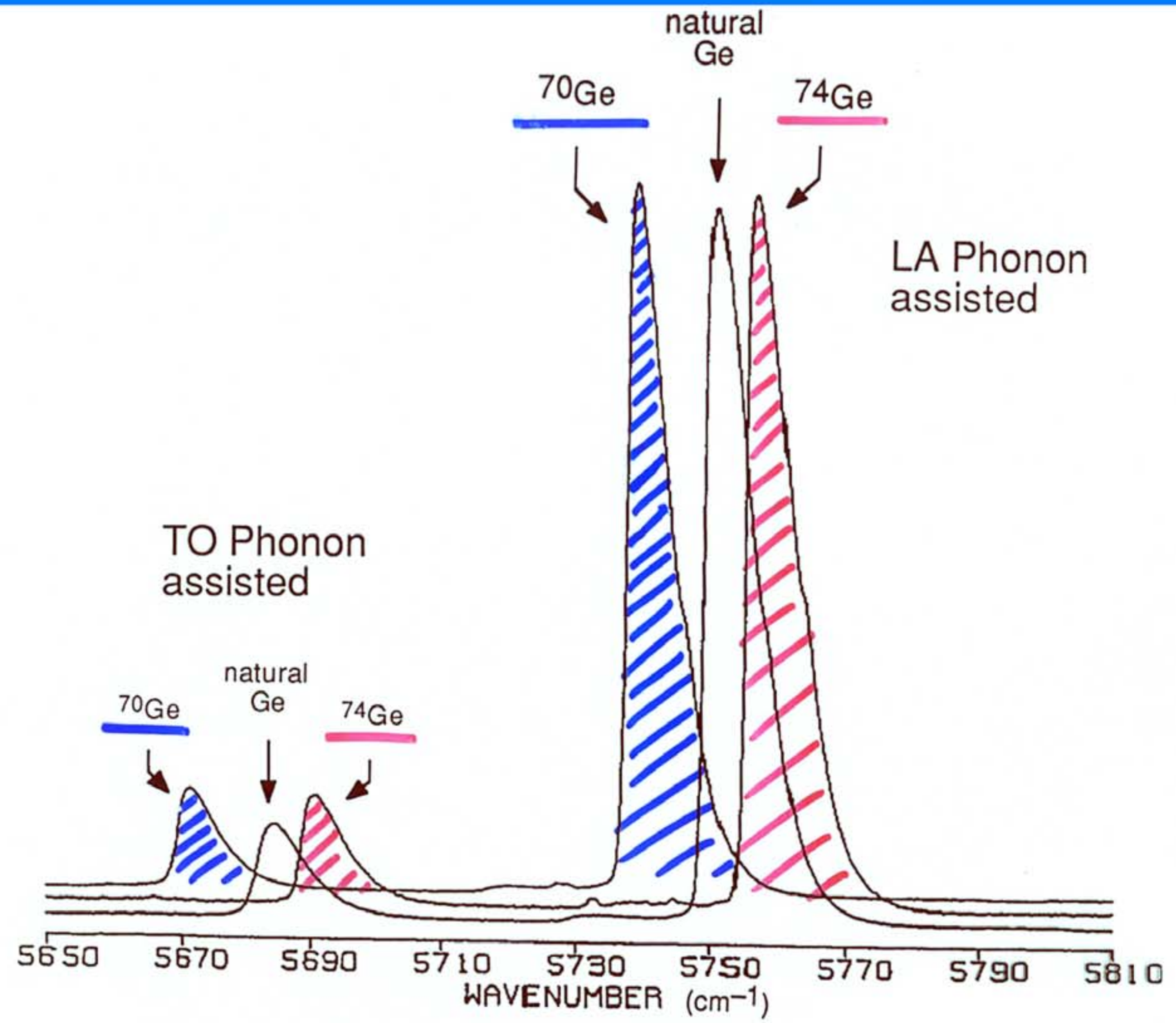


N



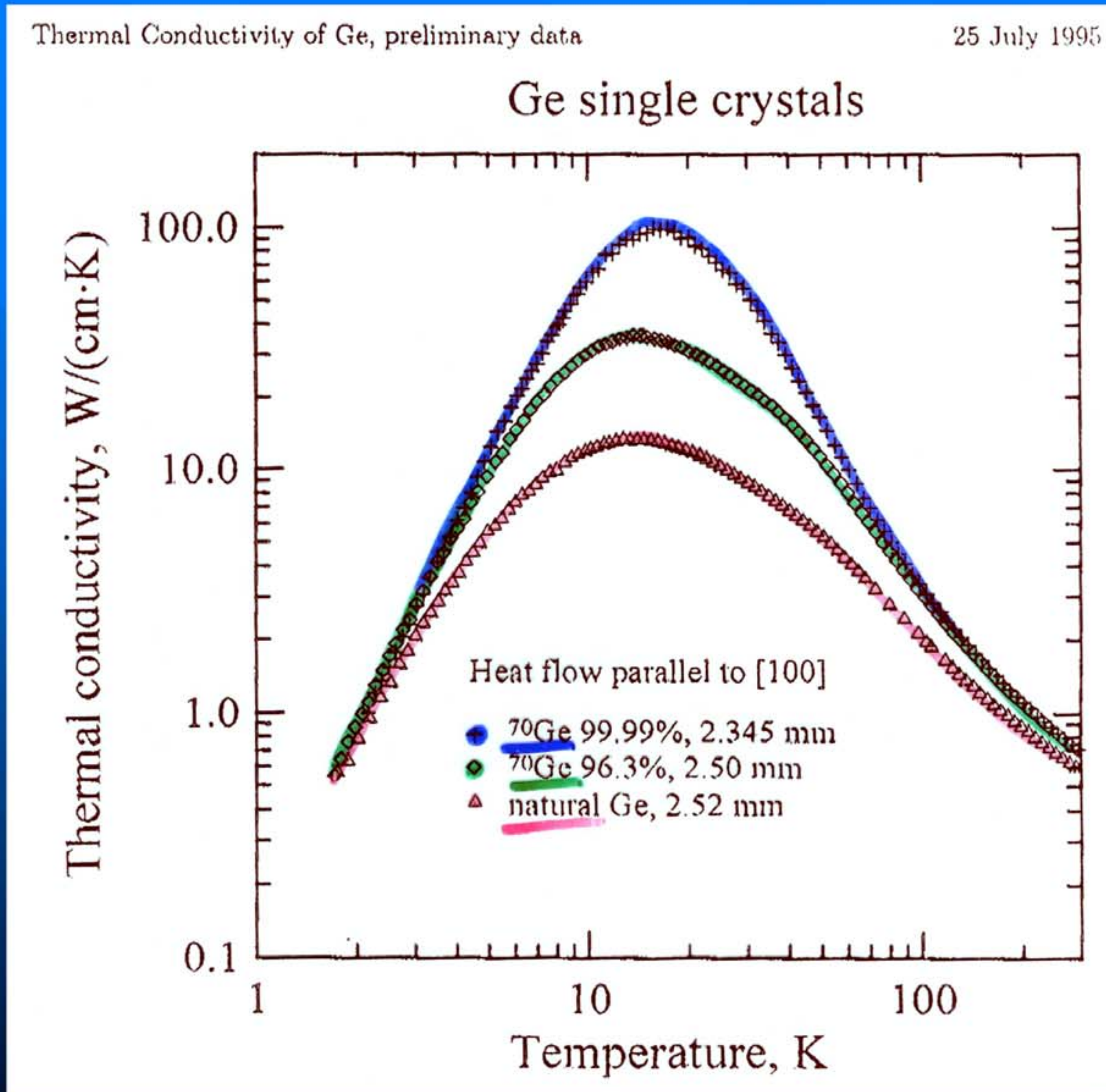
95% ENRICHED, ULTRA-PURE Ge SINGLE CRYSTALS

Excitons in ^{70}Ge, $^{nat.}$Ge and ^{74}Ge



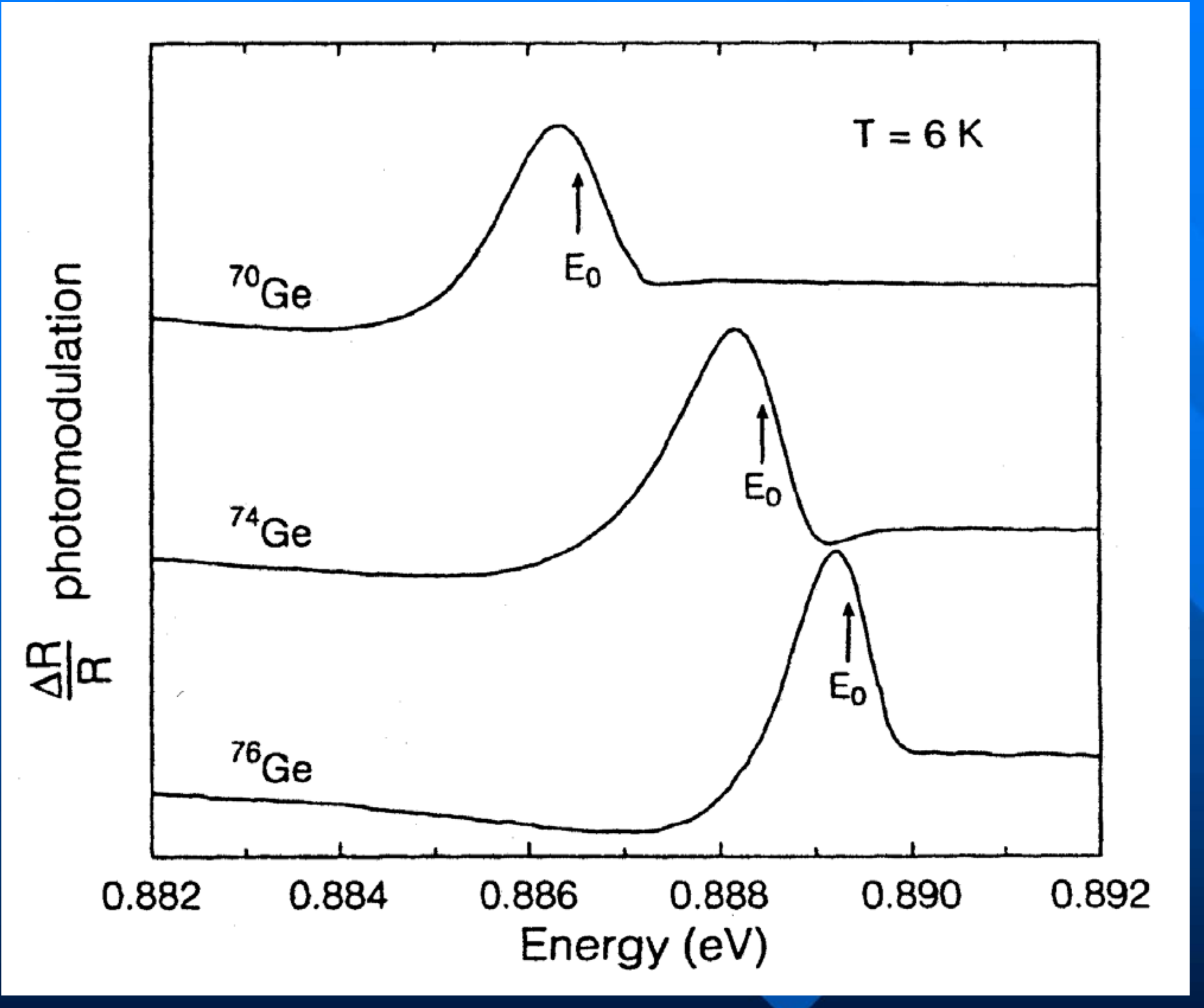
Free Exciton Emission from ^{70}Ge, ^{74}Ge and natural Ge
(King's College London, Oct. 20, 1991)

Thermal Conductivity of Solids



Valery Ozhogin and Alexander Inyushkin, Kurchatov Institute, Moscow

Change of the direct Ge Bandgap with Isotope Mass

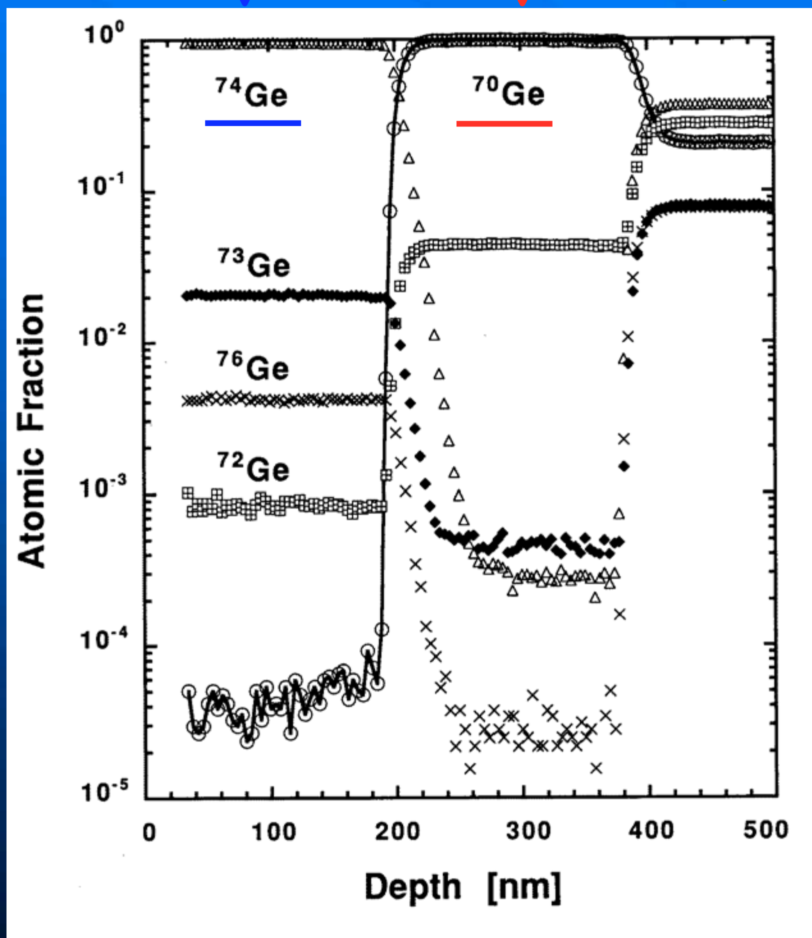


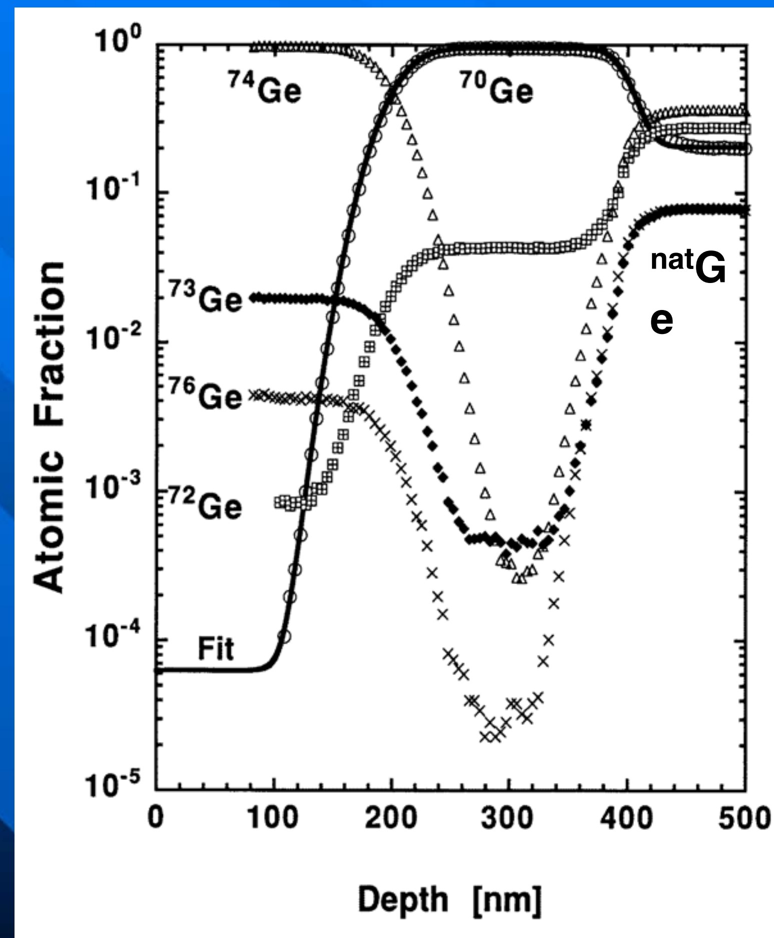
C. Parks, *et al.*, Phys. Rev B. **49**, 14244 (1994)

Self-Diffusion in Isotope Structures

^{74}Ge (> 96%)	^{70}Ge (> 95%)	^{nat}Ge

After annealing (55 hrs / 586˚C)





H. Fuchs *et al.*, Phys. Rev. B **51**, 16871 (1995)

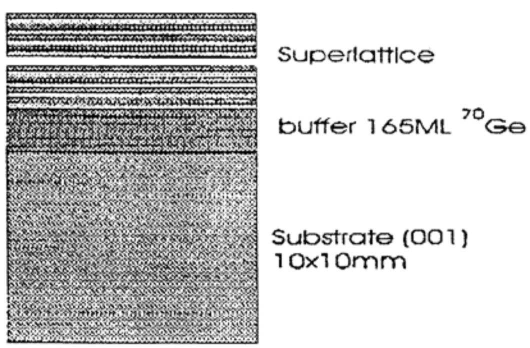
The First Ge Isotope Superlattice

Isotopic superlattices 23.09.1993

Sample	Structure
1Gi21-1	$^{70}Ge_8{}^{74}Ge_8$ 25 periods on (001) substrate
1Gi21-2	$^{70}Ge_2{}^{74}Ge_2$ 100 periods on (001) substrate
1Gi21-3	$^{70}Ge_{16}{}^{74}Ge_{16}$ 13 periods on (001) substrate
1Gi21-5	$^{70}Ge_4{}^{74}Ge_4$ 50 periods on (001) substrate
1Gi21-6	$^{70}Ge_{0.5}{}^{74}Ge_{0.5}$ 565 monolayers on (001) substrate
1Gi21-7	^{74}Ge 565 monolayers on (001) substrate

Sample	Structure
1Gi22-1	^{70}Ge 565 monolayers on (001) substrate
1Gi22-2	$^{70}Ge_6{}^{74}Ge_6$ 35 periods on (001) substrate
1Gi22-3	$^{70}Ge_{12}{}^{74}Ge_{12}$ 17 periods on (001) substrate
1Gi22-4	$^{70}Ge_{32}{}^{74}Ge_{32}$ 7 periods on (001) substrate
1Gi22-5	$^{70}Ge_{16}{}^{74}Ge_{16}$ 13 periods on (001) substrate grown at 270°C
1Gi22-6	1000 Å ^{74}Ge on 1000 Å ^{70}Ge
1Gi22-7	$^{70}Ge_{16}{}^{74}Ge_{16}$ 13 periods on (001) substrate grown at 210°C

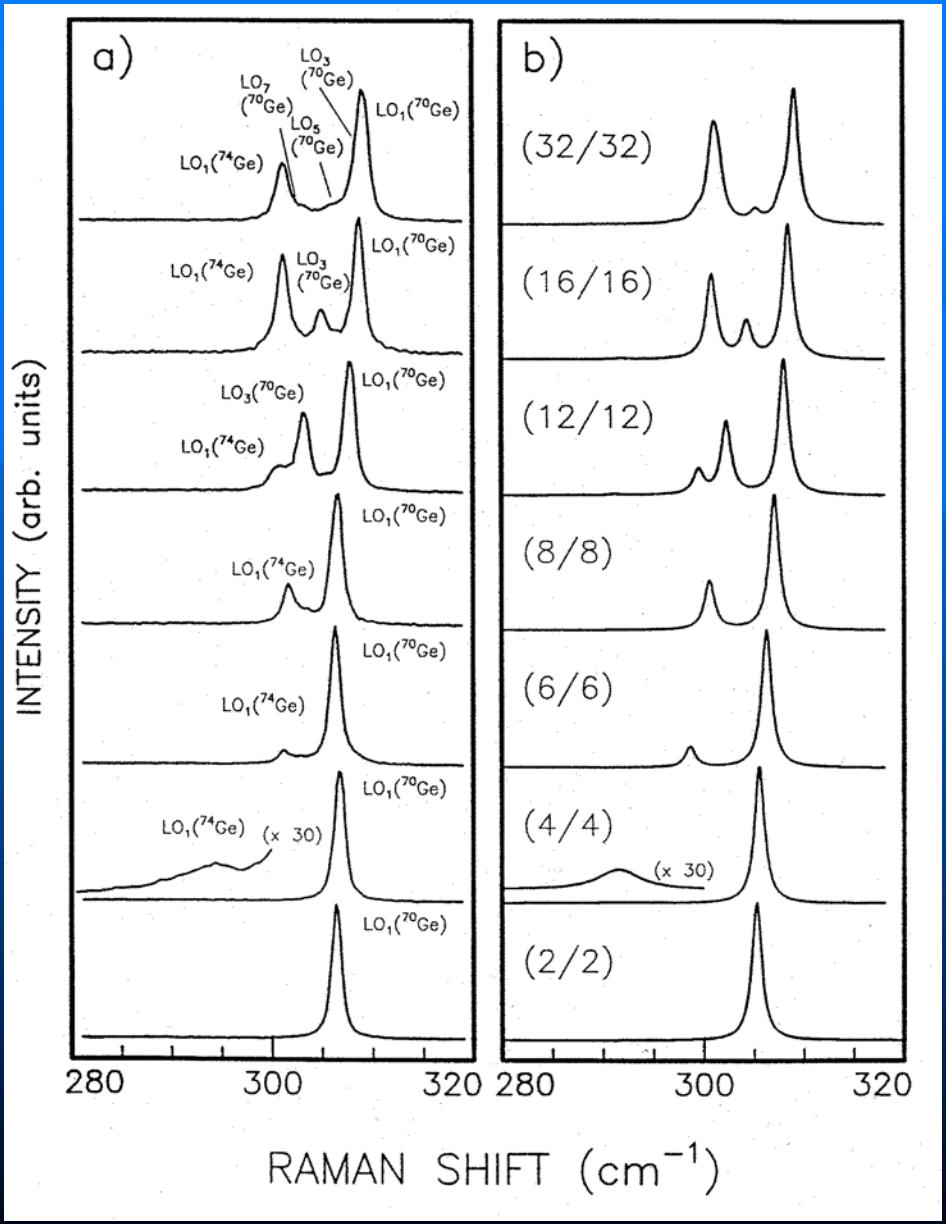
superlattice samples have a 165ML bufferlayer of ^{70}Ge to bury C-contamination.
Growth temperature was by default 350°C.



G. Abstreiter, Munich

Raman Lines of the Ge Isotope Superlattice

Experiment



Theory

Spitzer, *et al.*, Phys. Rev. Lett. **72**, 1565 (1994)

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- Germanium Speeds Up Silicon Transistors

IEEE ELECTRON DEVICE LETTERS, VOL. 27, NO. 7, JULY 2006 567

Half-Terahertz Operation of SiGe HBTs

Ramkumar Krithivasan, Yuan Lu, John D. Cressler, *Fellow, IEEE*, Jae-Sung Rieh, *Senior Member, IEEE*, Marwan H. Khater, *Member, IEEE*, David Ahlgren, and Greg Freeman

***Abstract*—This letter presents the first demonstration of a silicon–germanium heterojunction bipolar transistor (SiGe HBT) capable of operation above the one-half terahertz (500 GHz) frequency. An extracted peak unity gain cutoff frequency (f_T) of 510 GHz at 4.5 K was measured for a $0.12 \times 1.0\ \mu m^2$ SiGe HBT (352 GHz at 300 K) at a breakdown voltage BV_{CEO} of 1.36 V (1.47 V at 300 K), yielding an $f_T \times BV_{CEO}$ product of 693.6 GHz-V at 4.5 K (517.4 GHz-V at 300 K).**

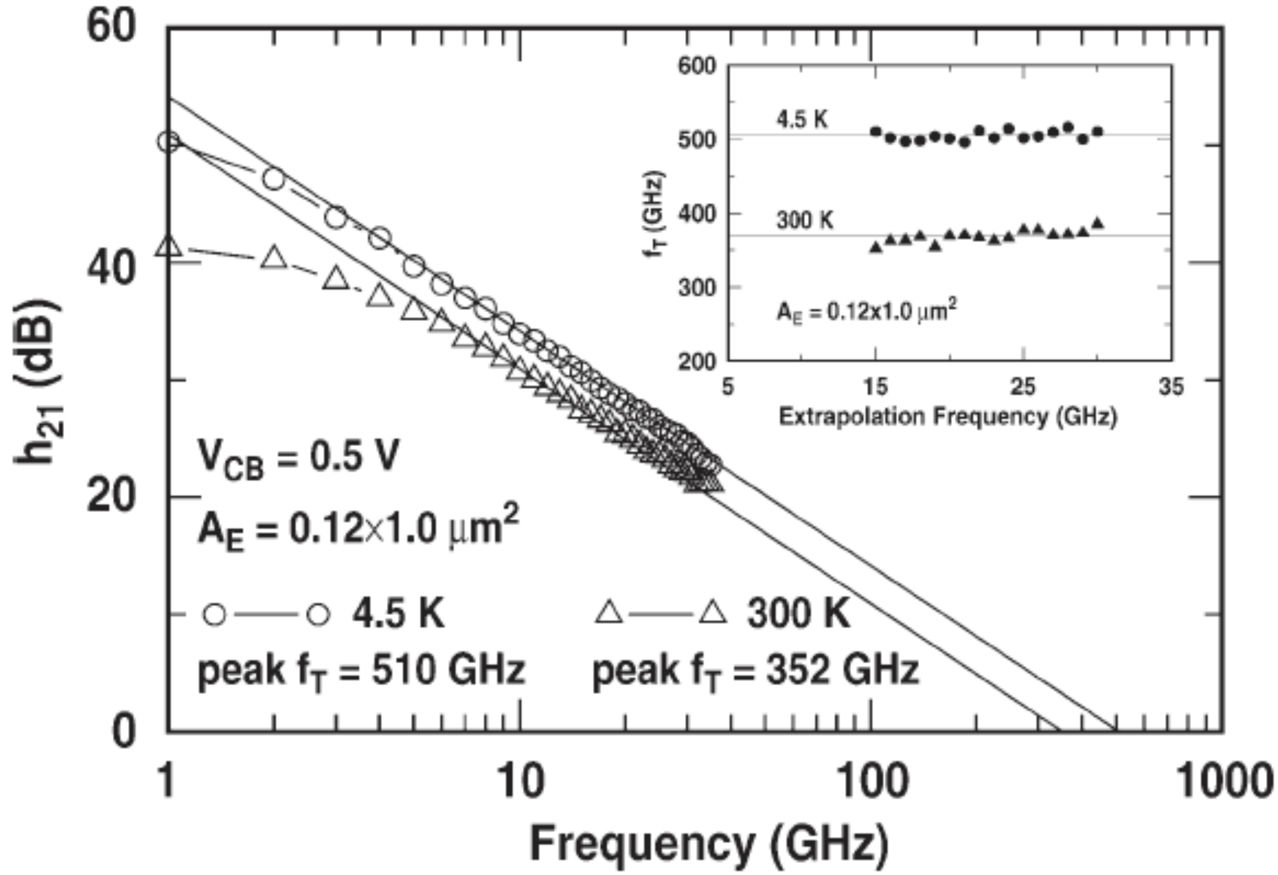


Fig. 3. Small-signal current gain at 300 and 4.5 K for a $0.12 \times 1.0\ \mu m^2$ SiGe HBT at peak f_T. Inset shows the inferred f_T as a function of extrapolation frequency.

1840 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 53, NO. 8, AUGUST 2006

Physics of Hole Transport in Strained Silicon MOSFET Inversion Layers

Everett X. Wang, *Member, IEEE*, Philippe Matagne, Lucian Shifren, Borna Obradovic, Roza Kotlyar, Stephen Cea, *Member, IEEE*, Mark Stettler, *Member, IEEE*, and Martin D. Giles, *Fellow, IEEE*

***Abstract*—A comprehensive quantum anisotropic transport model for holes was used to study silicon PMOS inversion layer transport under arbitrary stress. The anisotropic band structures of bulk silicon and silicon under field confinement as a two-dimensional quantum gas are computed using the pseudopotential method and a six-band stress-dependent k.p Hamiltonian. Anisotropic scattering is included in the momentum-dependent scattering rate calculation. Mobility is obtained from the Kubo–Greenwood formula at low lateral field and from the fullband Monte Carlo simulation at high lateral field. Using these methods, a comprehensive study has been performed for both uniaxial and biaxial stresses. The results are compared with device bending data and piezoresistance data for uniaxial stress, and device data from strained Si channel on relaxed SiGe substrate devices for biaxial tensile stress. All comparisons show a very good agreement with simulation. It is found that the hole band structure is dominated by 12 "wings," where mechanical stress, as well as the vertical field under certain stress conditions, can alter the energies of the few lowest hole subbands, changing the transport effective mass, density-of-states, and scattering rates, and thus affecting the mobility.**

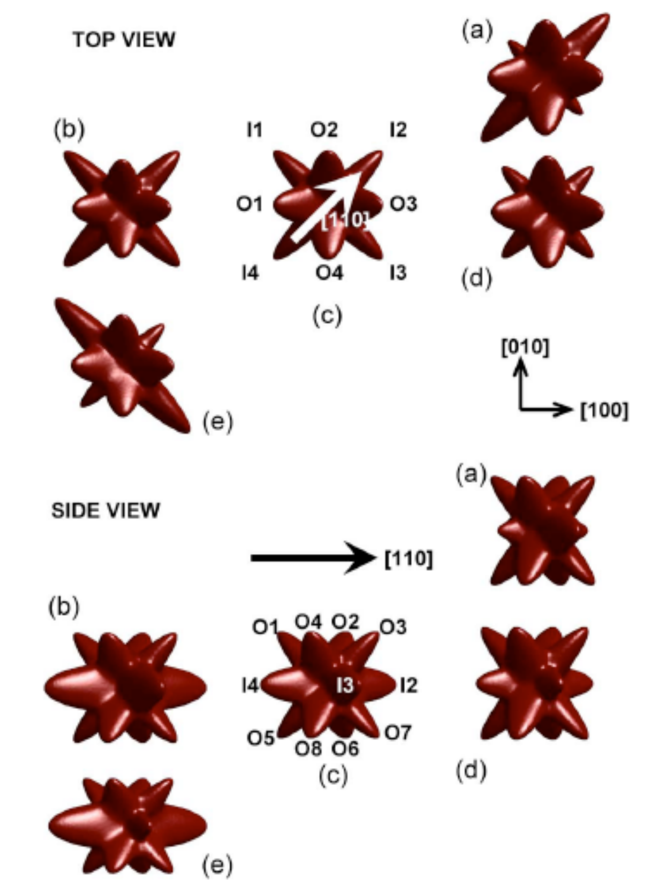


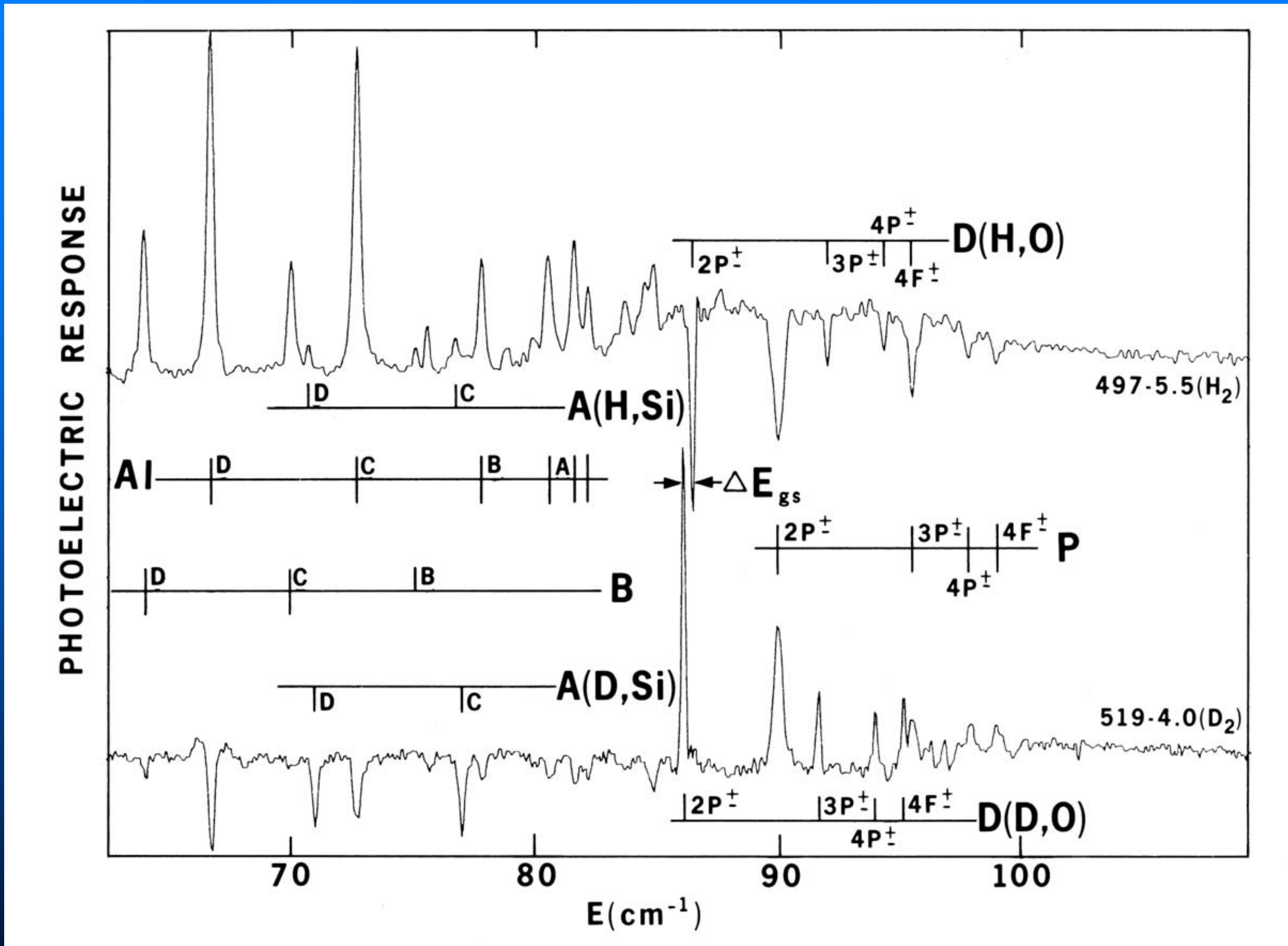
Fig. 1. Top and side views of bulk hh iso-surfaces at 100 meV under (a) [110] tensile 1 GPa, (b) biaxial compressive 1 GPa, (c) no stress, (d) biaxial tensile 1 GPa, and (e) [110] compressive 1 GPa. (Color version available online at http://ieeexplore.ieee.org.)

Summary

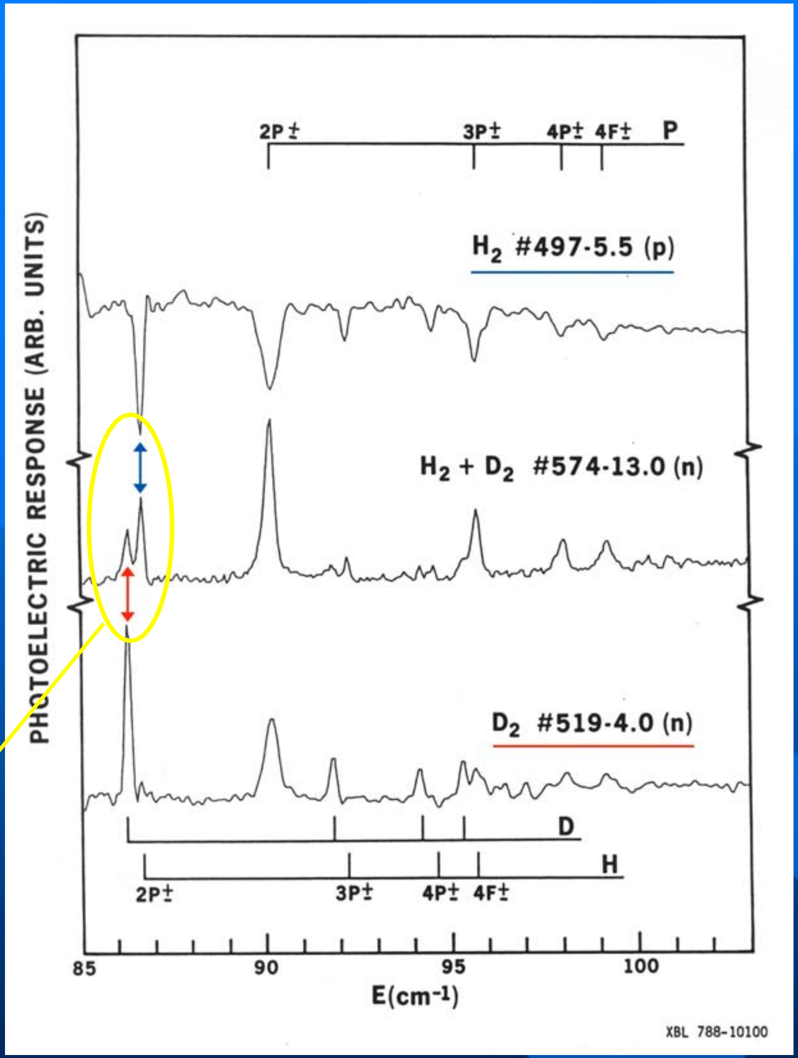
- The 120 year history of the element Ge is rich in science and technology
- Today Ge has returned to mainstream electronics because of its excellent transport properties and engineering of bandstructures using strain
- More interesting findings will be made…Long live Germanium!

Thanks for your Attention

EXTRAS



PHOTOELECTRIC RESPONSE
D(H,O)
A(H,Si)
Al
ΔE_{gs}
P
B
A(D,Si)
D(D,O)
497-5.5(H$_2$)
519-4.0(D$_2$)
70
80
90
100
E(cm^{-1})



Pure H_2 atmosphere

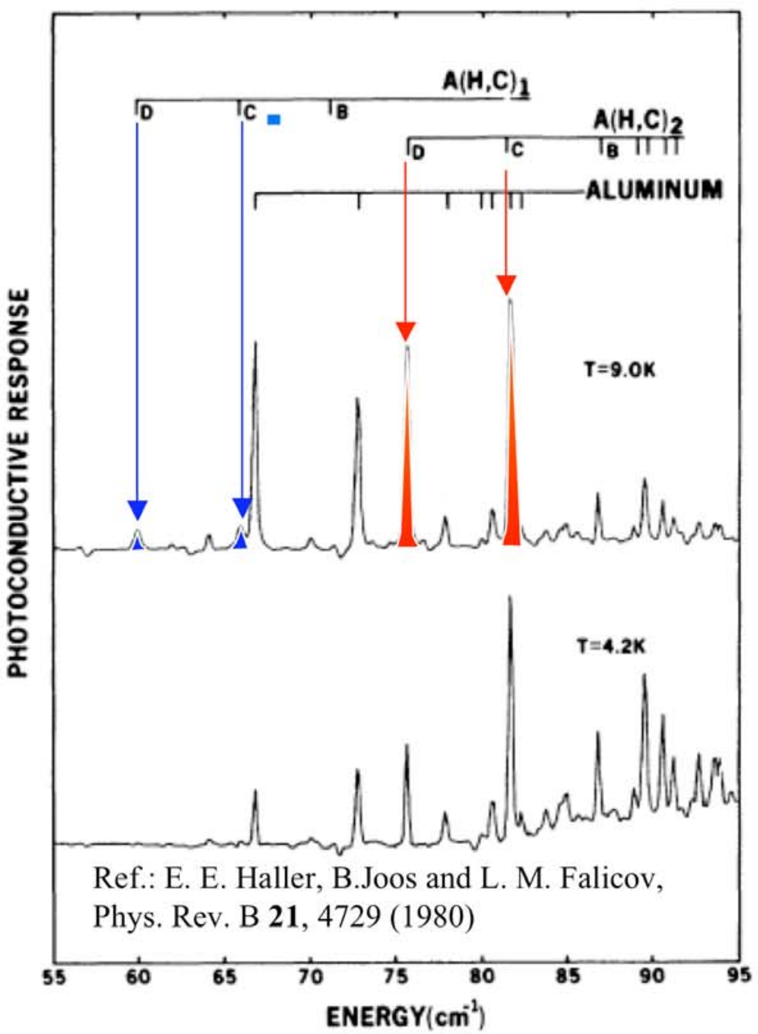
Mixed atmosphere:
H/D = 1/1

Pure D_2 atmosphere

∴ **The D(O,H) donor in Ge contains exactly one H atom!**

Ref.: E. E. Haller, Inst. Phys. Conf. Series **46**, 205 (1979)

The Acceptor A(H,C) in Ultra-Pure Germanium



Ref.: E. E. Haller, B.Joos and L. M. Falicov, Phys. Rev. B **21**, 4729 (1980)

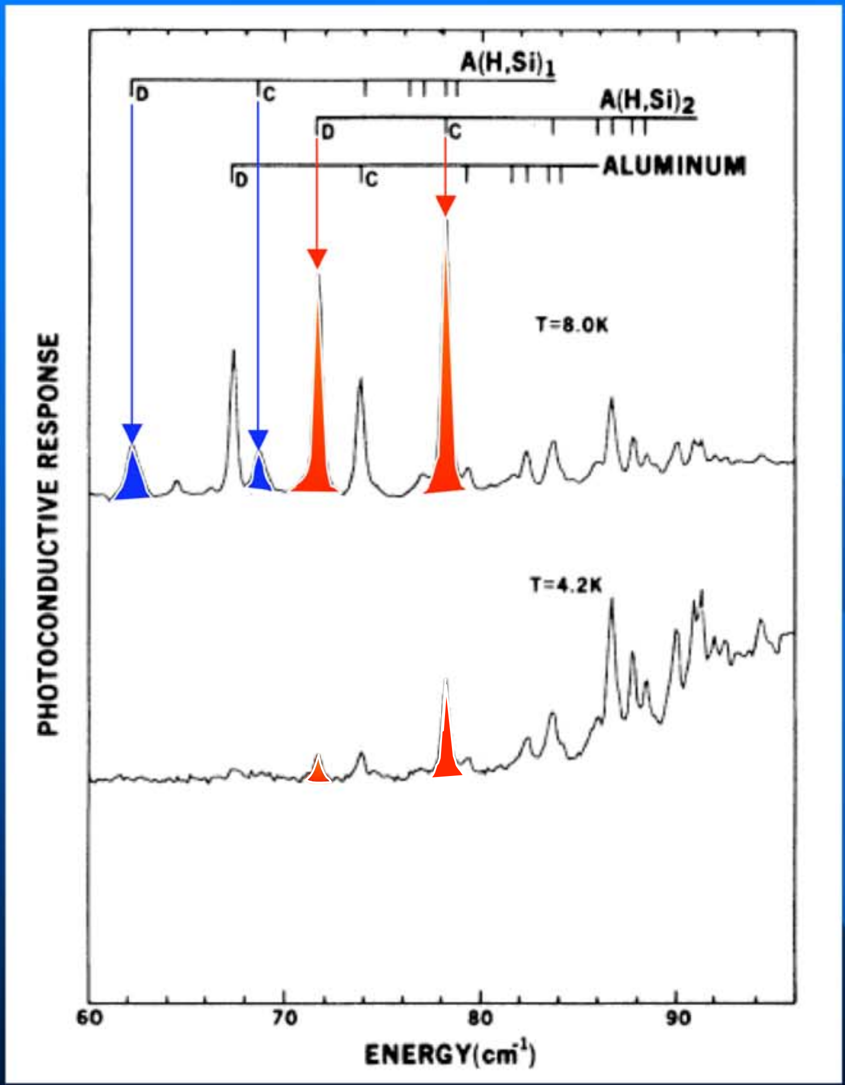
•The groundstate of A(H,C) is split by 1.98 meV, leading to two series of ground-to-bound excited state line series (blue and red). The intensity ratio of corresponding lines is proportional to a Boltzmann factor exp [1.98 meV/k_BT].

• Only crystals grown in a H_2 atmosphere from a graphite crucible contain this acceptor.

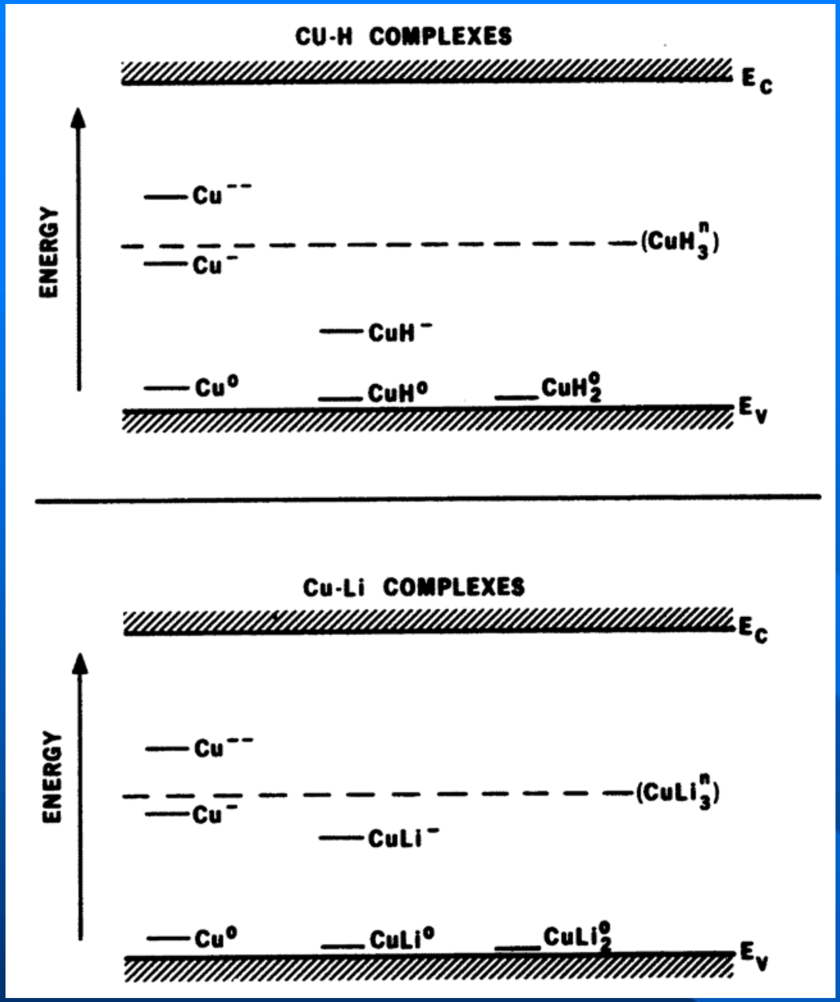
• Upon substitution of H with D the ground state shifts by 51 µeV to lower energies.

• Joos et al., Phys. Rev. B **22**, 832 (1980) modeled this center with a tunneling hydrogen complex.

The Acceptor A(H,Si) in Ultra-Pure Germanium

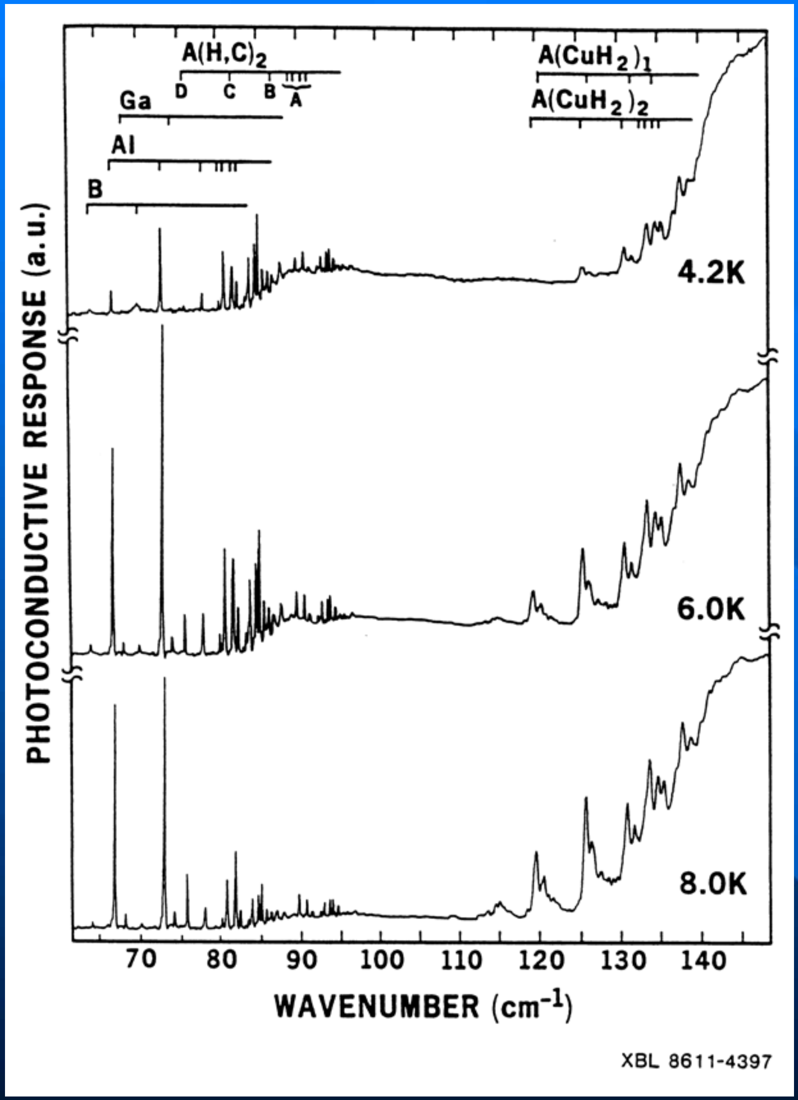


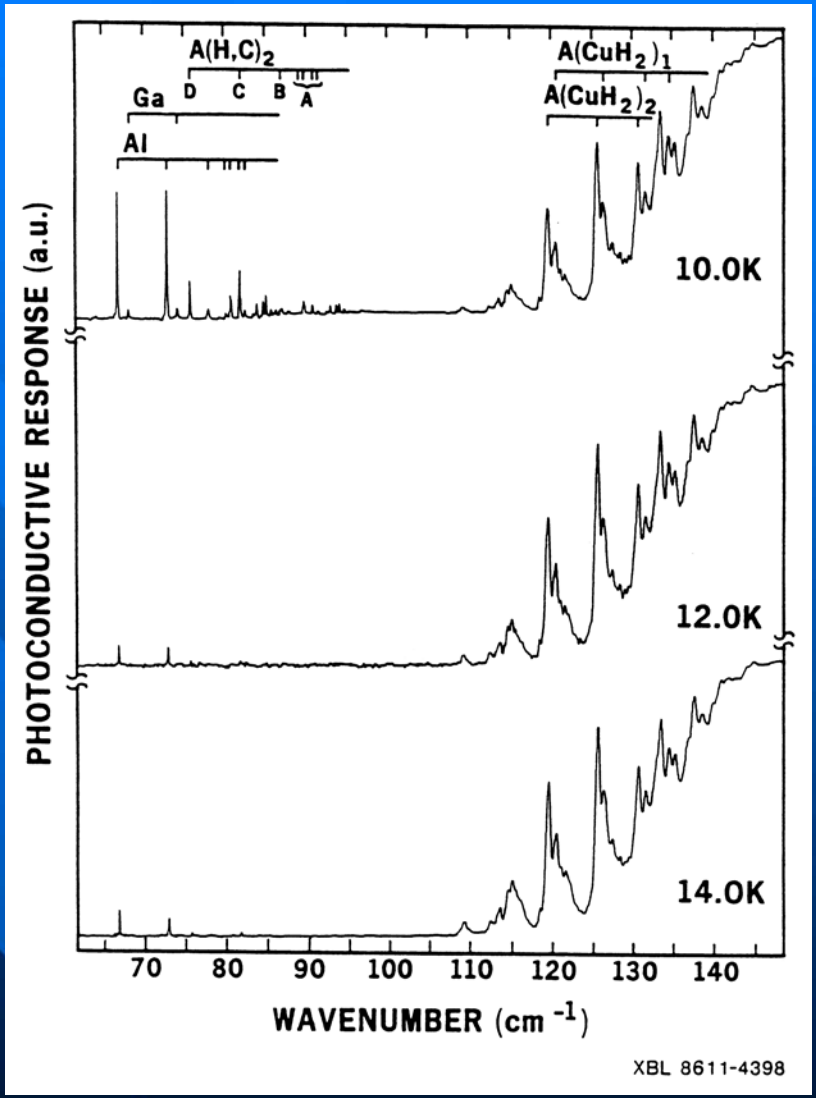
- The groundstate of A(H,Si) is split by 1.07 meV, leading to two series of ground-to-bound excited state line series (blue and red). The intensity ratio of corresponding lines is proportional to a Boltzmann factor exp [1.1 meV/k_BT].
- Only crystals grown in a H_2 atmosphere from a SiO_2 crucible contain this acceptor.
- Upon substitution of H with D the ground state shifts by 21 μeV to lower energies.
- Kahn et al., Phys. Rev. B **36**, 8001 (1987) modeled this and other centers [A(H,C), A(Be,H), A(Zn,H)] with trigonal complexes.



The *Cu triple acceptor in Ge* binds up to three interstitial H or Li atoms. Each bound H or Li reduces the number of electronic states by one (i.e., CuH_3 is neutral)

Position of the acceptor levels of copper and its complexes with hydrogen and lithium in germanium. [Ref.: E.E. Haller, G.S. Hubbard and W.L. Hansen, *IEEE Trans. Nucl. Sci.* NS-**24**, No. 1, 48 (1977)]

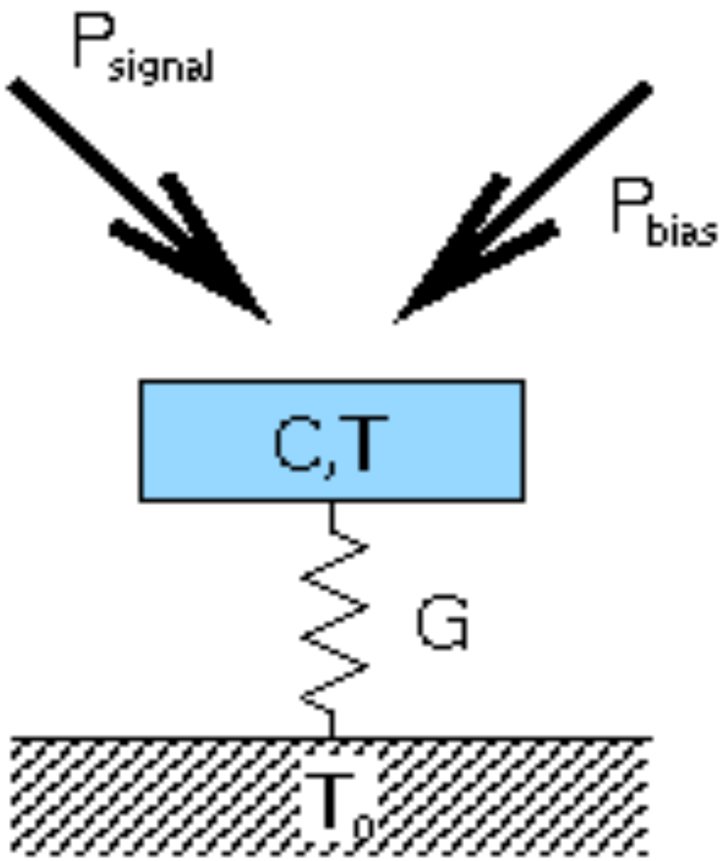

A(H,C)$_2$
D C B A
Ga
Al
B
A(CuH$_2$)$_1$
A(CuH$_2$)$_2$
4.2K
6.0K
8.0K
PHOTOCONDUCTIVE RESPONSE (a.u.)
70 80 90 100 110 120 130 140
WAVENUMBER (cm^{-1})
XBL 8611-4397


A(H,C)$_2$
D C B A
Ga
Al
A(CuH$_2$)$_1$
A(CuH$_2$)$_2$
10.0K
12.0K
14.0K
PHOTOCONDUCTIVE RESPONSE (a.u.)
70 80 90 100 110 120 130 140
WAVENUMBER (cm $^{-1}$)
XBL 8611-4398

Hillocks or dimples?

Neutron Transmutation Doped Ge Thermistors for Bolometers

Bolometers have two components: an absorber (TeO_2) and a thermometer (NTD Ge)



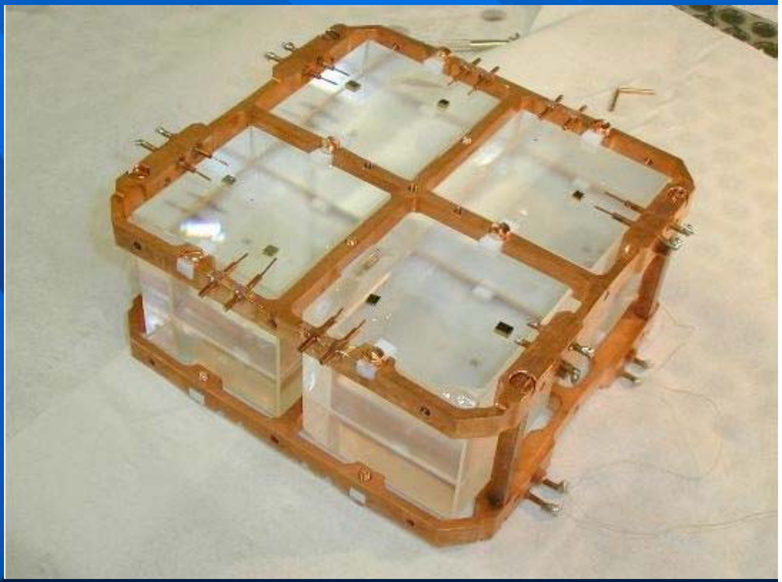
- Thermometer and absorber (heat capacity C) are connected by a weak thermal link (G) to a heat sink (T_o)
- Incoming energy is converted to heat in the absorber:

  $T=T_o + (P_{signal} + P_{bias})/C$

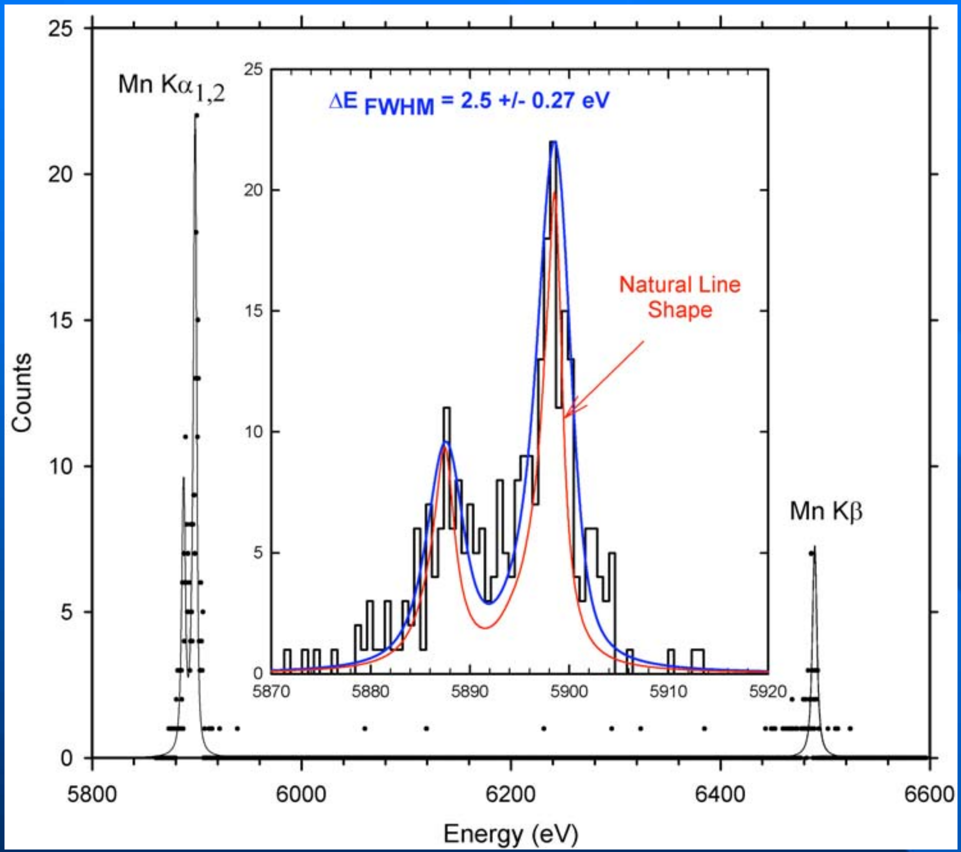
- Temperature rise is proportional to the incoming energy
- Temperature rise decays as energy flows from the absorber to heat sink: $\tau = C/G$

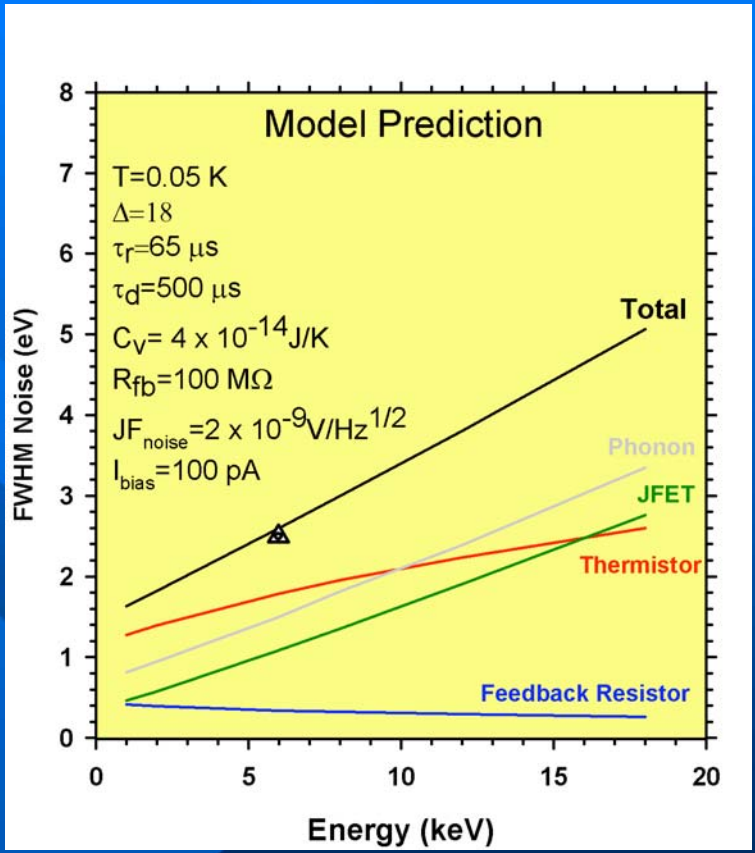
CUORE/CUORICINO Double Beta Decay: An Italian-US Experiment

- Absorber: TeO_2 single crystals, ~ 1000 kg
- Temperature: 5 mK
- Thermal Sensors: NTD Ge
- Support: Copper, Teflon



X-Ray Performance: Single X-Ray Counting





0.35 mm x 0.35 mm x 7 µm tin absorber + NTD 17 Ge thermistor

A publication describing an earlier measurement of 3.08 eV is: E. Silver, J. Beeman, F. Goulding, E.E. Haller, D. Landis and N. Madden, *Nuclear Instruments and Methods in Physics Research*, Volume **545**, 3, (2005), 683-689.

Courtesy Eric Silver, Harvard

II. SiGe HBT TECHNOLOGY

The device structure utilized here for this prototype fourth-generation SiGe HBT is very similar topologically to that of a commercially available third-generation device, and utilizes a reduced-thermal-cycle "raised-extrinsic-base" structure [8]. The device is deep- and shallow-trench isolated, has an *in situ* phosphorus-doped polysilicon emitter, and a compositionally graded, carbon-doped, unconditionally stable, 25% peak Ge concentration, ultrahigh vacuum (UHV)/CVD SiGe base. Aggressive vertical profile scaling and careful collector implant tailoring were used to maximize f_T. This device is 100% silicon (CMOS) fabrication compatible and was fabricated on a 200-mm wafer.

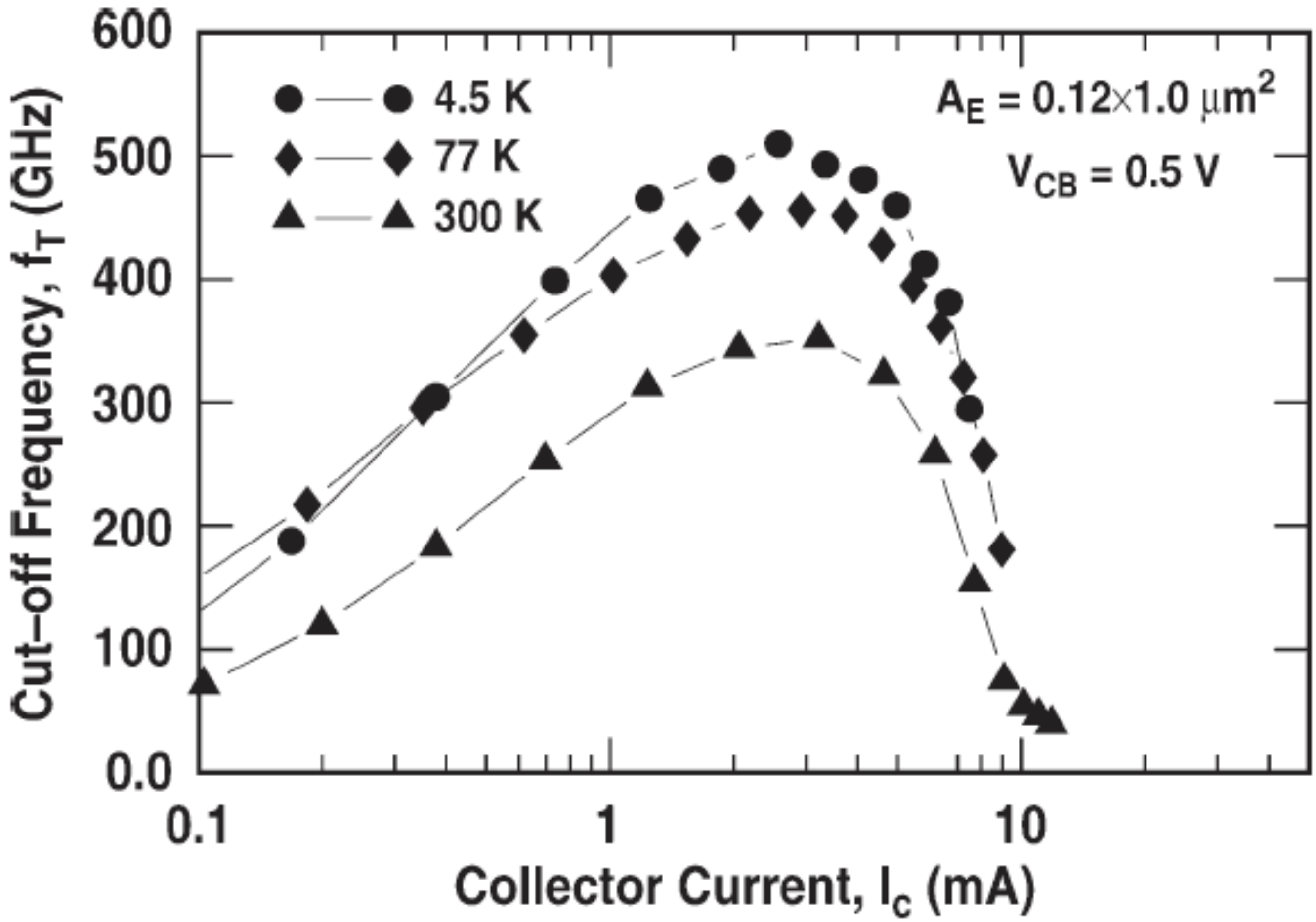


Fig. 4. Measured peak f_T as a function of bias current for a $0.12 \times 1.0\ \mu m^2$ SiGe HBT at 300, 77, and 4.5 K ($V_{CB} = 0.5$ V).

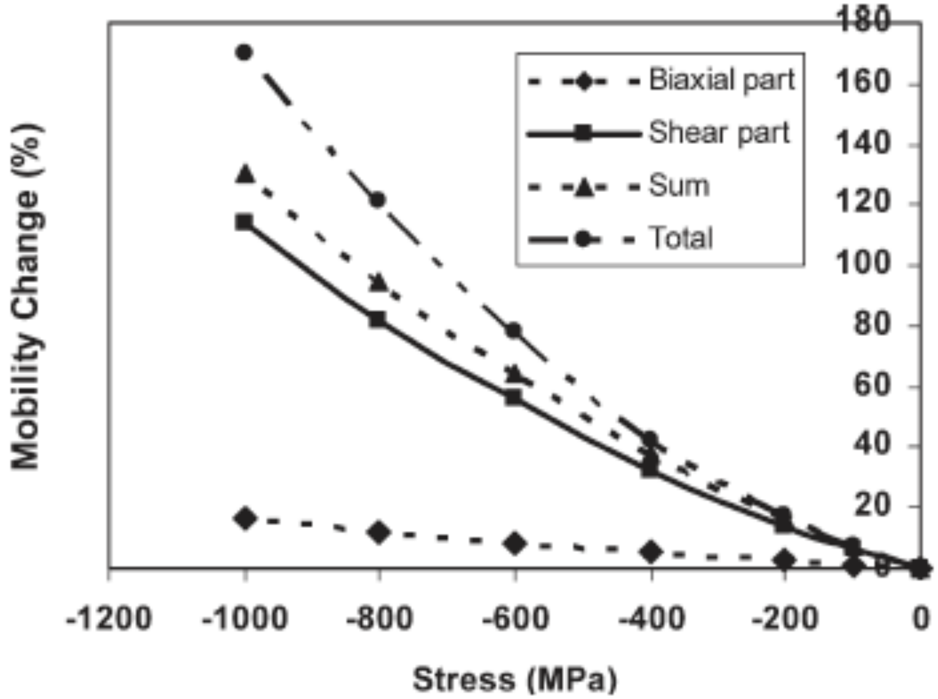


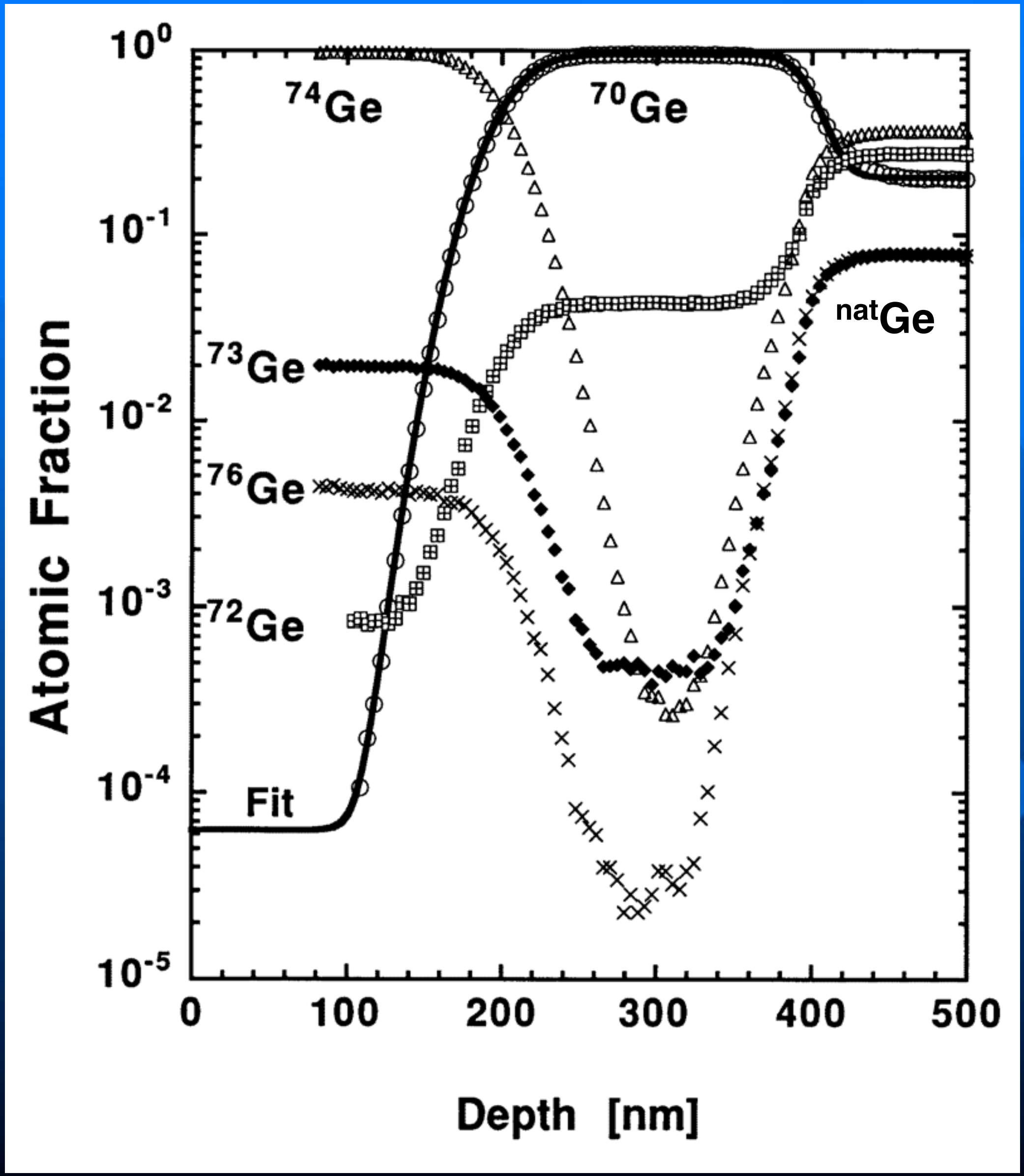
Fig. 13. Contributions from biaxial and shear components of a uniaxial compression along the channel direction. The shear component contributes the majority of the gain for uniaxial stress and the gains from shear and biaxial add nonlinearly.

H. Mataré 2003

H. Welker 1970

Working in Paris at the Westinghouse research laboratories, Herbert Mataré and Heinrich Welker made transistor observations using multipoint contacts. Welker went on to discover III-V compound semiconductors in the early 1950s, opening the world of optoelectronics.

After annealing (55 hrs / 586˚C)



H. Fuchs *et al.*, Phys. Rev. B **51**, 16871 (1995)

A High-Mobility Germanium QWFET

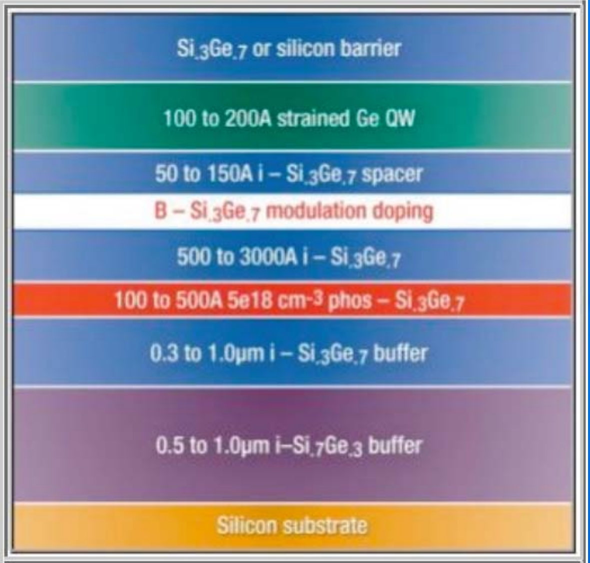


Figure 1: Biaxially strained undoped germanium quantum well structure on a silicon substrate. *(Source: Intel)*

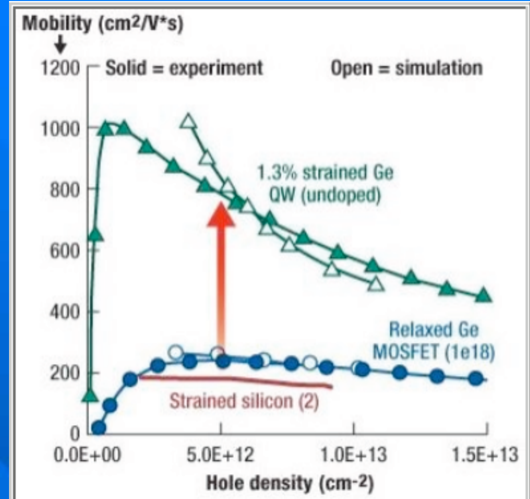


Figure 2: Hole mobility vs. density for strained silicon, a relaxed Ge MOSFET reference and the strained Ge quantum well FET. The data matches simulations assuming interface defect density and surface roughness matches that of state-of-the-art silicon devices. *(Source: Intel)*

December 6, 2010 - At IEDM 2009, Intel announced a record breaking quantum well field effect transistor (QWFET); a 35nm gate length device capable of 0.28mA/µm drive current and peak transconductance of 1350µS/µm. These QWFETs used InGaAs as the quantum well channel material. At this week's IEDM 2010 in San Francisco, Intel (Hillsboro, OR) will again demonstrate a first: a high-mobility germanium QWFET that achieves the highest mobility (770 cm2/Vsec) with ultrathin oxide Thickness (14.5Å) for low-power CMOS applications. This hole mobility is 4× higher than that achieved in state-of-the-art p-channel strained silicon devices. These results involve the first demonstration of significantly superior mobility to strained silicon in a p-channel device for low-power CMOS. The biaxially strained germanium QW structure (Figure) 1 incorporates a phosphorus doped layer to suppress parallel conduction in the SiGe buffers.