John Bardeen and Transistor Physics

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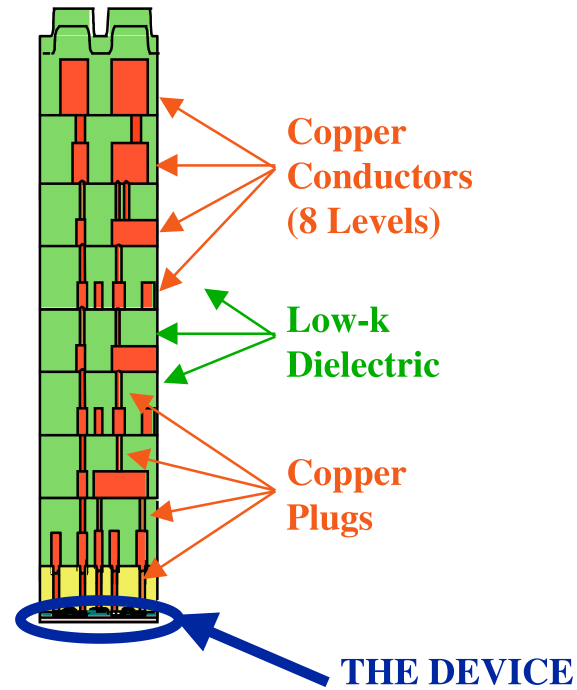
Agenda

- Introduction
- Schottky-barrier diode
  - Rectification
- Point-contact semiconductor amplifier
  - Field effect / surface states
  - Minority carriers
  - Surface-states control
  - Magic month: Nov 17 ‘47 - Dec 16 ‘47
  - Historic day- Dec 16 ‘47
  - Recapitulation / Serendipity Factors
  - Naming invention / patents
- Bipolar junction transistor
  - Magic month: Dec 24 ‘47- Jan 23 ‘48
  - Implementation
- Contemporaneous Events
- Modern silicon MOSFETs
- Summary
- Acknowledgements

100 nm High End Microprocessor



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Introduction

- **Point-contact semiconductor amplifier (transistor action), evolved (significantly) from studies on Shockley's field-effect principle**
  - Invented by Bardeen and Brattain on December 16, 1947, for which they received a patent on October 3, 1950
- **Shockley not co-patent holder with Bardeen and Brattain since his scientific contribution of field-effect principle anticipated through previous patent awarded to Lilienfeld in 1930**
  - Bardeen also received on October 3rd patent for essence of MOS transistor, what Sah called sourceless MOS transistor, utilizing inversion layer as channel for confinement of minority carriers
- **John Bardeen, co-inventor of point-contact transistor and inventor of MOS transistor, may rightly be called *father* of modern electronics**
- **Nevertheless, Shockley deservedly shared Nobel prize with Bardeen and Brattain for seminal contributions of injection over barrier, p-n junction theory and p-n junction transistor**

Introduction
Bell Laboratories Goal

Controlling signals central to communication business

$\Downarrow$

Introduce solid-state devices in telephone system

$\Downarrow$

Replace vacuum tube amplifier and electro-mechanical relay switch by solid-state amplifier and switch, respectively

Introduction
Point-contact Semiconductor Amplifier

- **Schottky-barrier diode**
  - Point-contact rectifier
  - Metal-semiconductor junction
  - Surface-barrier diode
- **Bipolar transistor**
  - Point-contact transistor
  - Junction transistor
- **Metal oxide semiconductor field-effect transistor (MOSFET)**
  - Metal-oxide-silicon field-effect transistor (MOSFET)
  - Metal-oxide-semiconductor transistor (MOST)
  - Insulated-gate field-effect transistor (IGFET)

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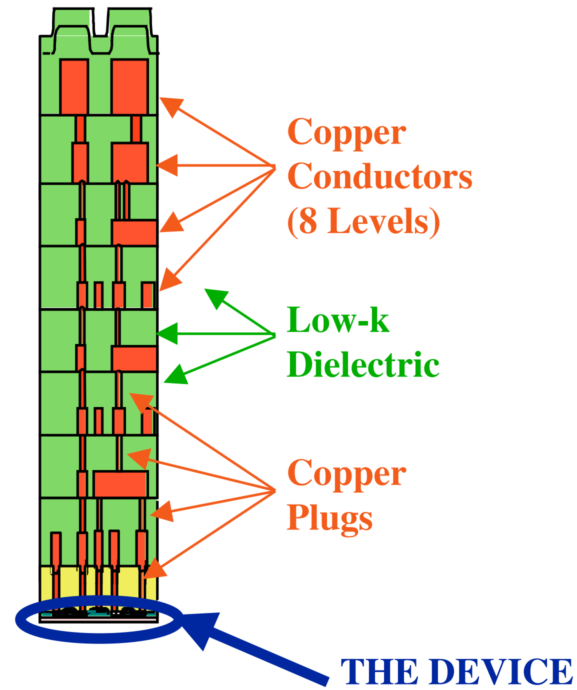

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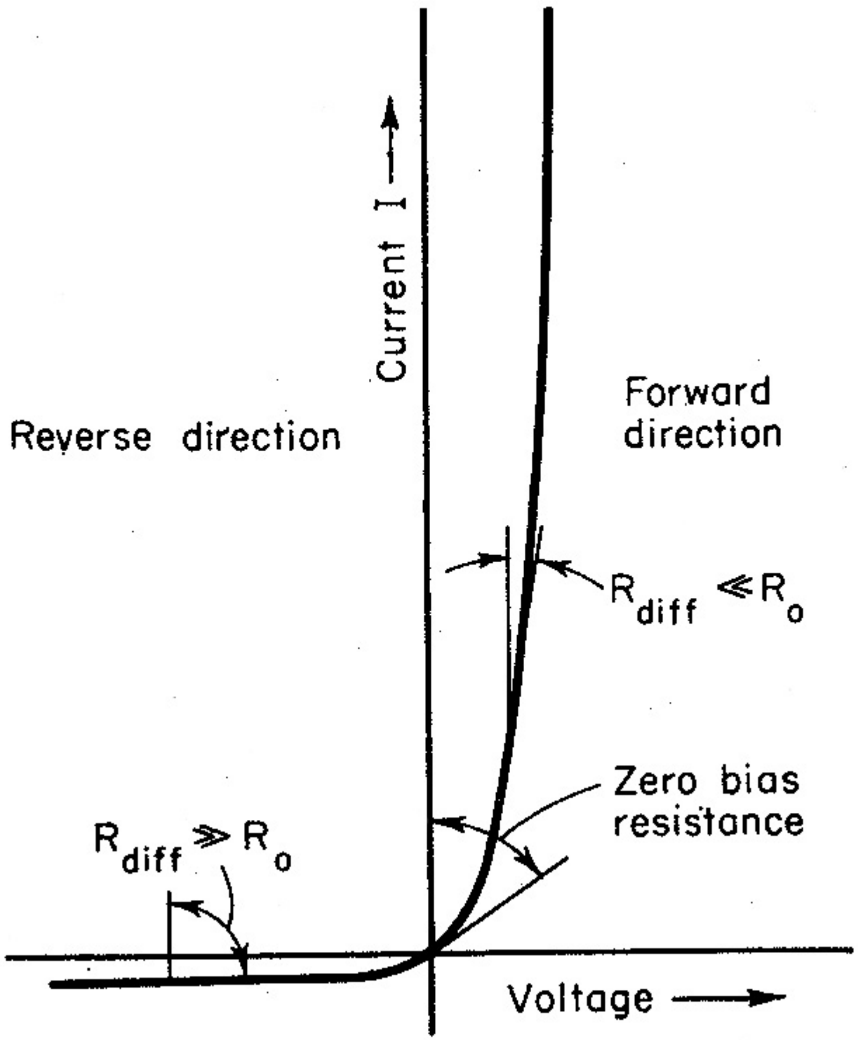
Schottky-Barrier Diode

Rectification

- **Passive device exhibiting asymmetric I-V characteristic**
  - Semiconductor device having two terminals and exhibiting nonlinear current-voltage characteristic
- **Appearance of voltage across rectifier upon illumination referred to as photovoltaic effect**
  - Observed in silicon by Ohl in 1940
  - Example of minority carrier introduction by optical process
  - Minority carrier introduction by thermal process also well known
- **Physical processes of rectification and photovoltaic effect intimately associated with interface between metal and semiconductor (or between two semiconductors) rather than distributed throughout semiconductor volume**
  - Barrier or interface layer about 10^{-4} - 10^{-3} cm
  - Metal contact ohmic and supplies current
- **Space-charge theory of rectification, also referred to as "one-current" theory of rectifiers successfully explained observations**
  - Schottky, Mott, Davydov and Bethe

Rectification Characteristic



After Spenke

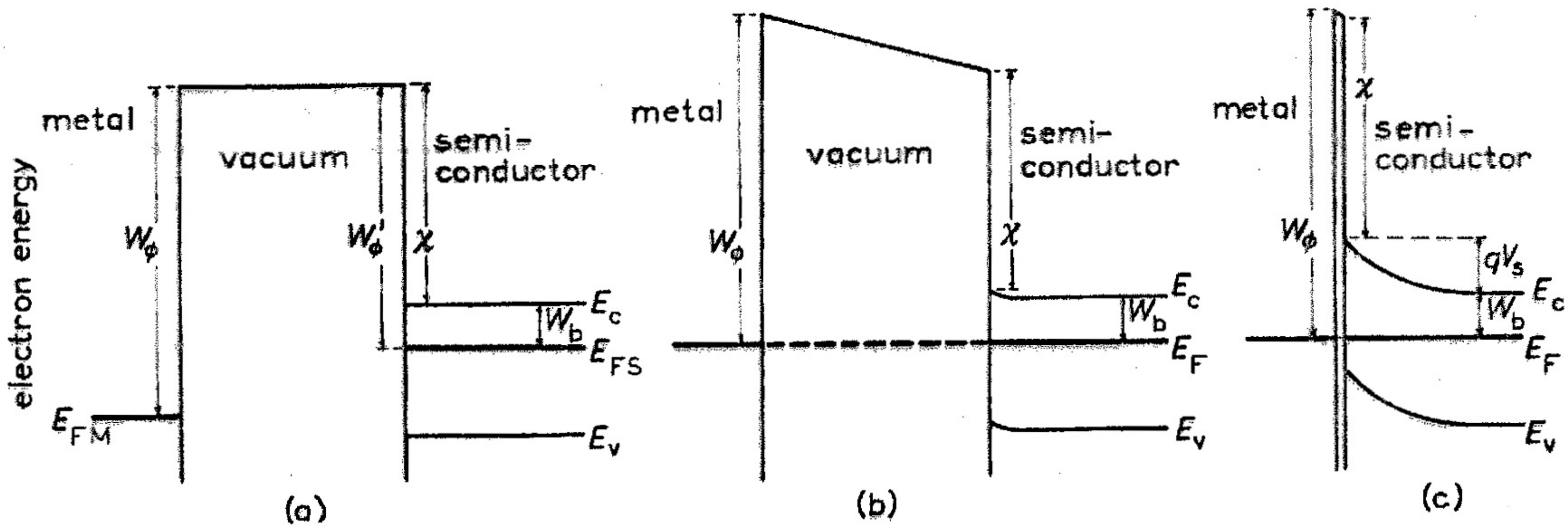
Bardeen / Schottky / Brattain - Pretzfeld, 1954

Sirtl

Rectification

- **Physical structure resulting in rectification characteristic modeled as difference in work functions, W_{ϕ}, between two solids**
  - W_{ϕ} energy to remove electron at E_F to point in free space just outside solid
  - Electrons transfer from solid with lower W_{ϕ} to solid with higher W_{ϕ} until thermal equilibrium attained ($E_{F1} = E_{F2}$)
  - Potential barrier, qV_s established in solid donating electrons
    - $qV_s = W_{\phi 1} - W_{\phi 2} \equiv$ contact potential (c.p.)
  - Space charge region, *SCR*, formed in both solids although greater in solid with smaller numbers of free carriers
    - Majority carriers depleted in semiconductor, leaving static, unscreened (+) ionized donors (metal/n-type semiconductor, $W_{sc} < W_m$) resulting in semiconductor energy bandbending $\Rightarrow$ surface-space-charge-region (*SSCR*)
    - Electron transfer continues until bulk electron diffusion exactly balanced by spatially varying internal electric field set up by energy-band bending
- **Correlation of qV_s with polarity/magnitude of c.p. not observed**
  - W_{ϕ} of metal made little or no difference

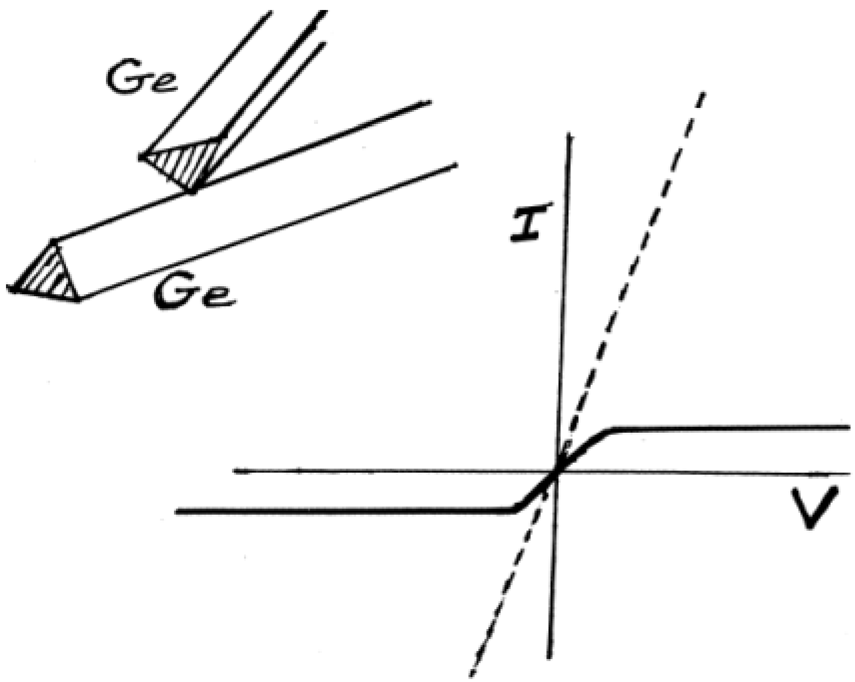
Energy -Level Diagram For Metal / N-Type Semiconductor With No Surface States



After Many, Goldstein and Grover

Semiconductor-Semiconductor Contact

- Germanium-germanium contacts (contact potential = 0) exhibited for both voltage polarities, I-V characteristic previously observed only for reverse characteristic
- Appears SSCR established at semiconductor surface by means other than contact potential difference



After Bray

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- ➢ **Acknowledgements**

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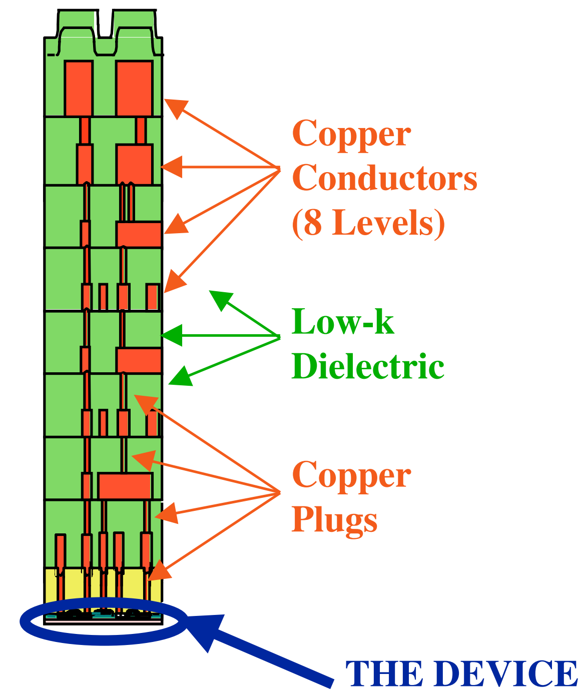

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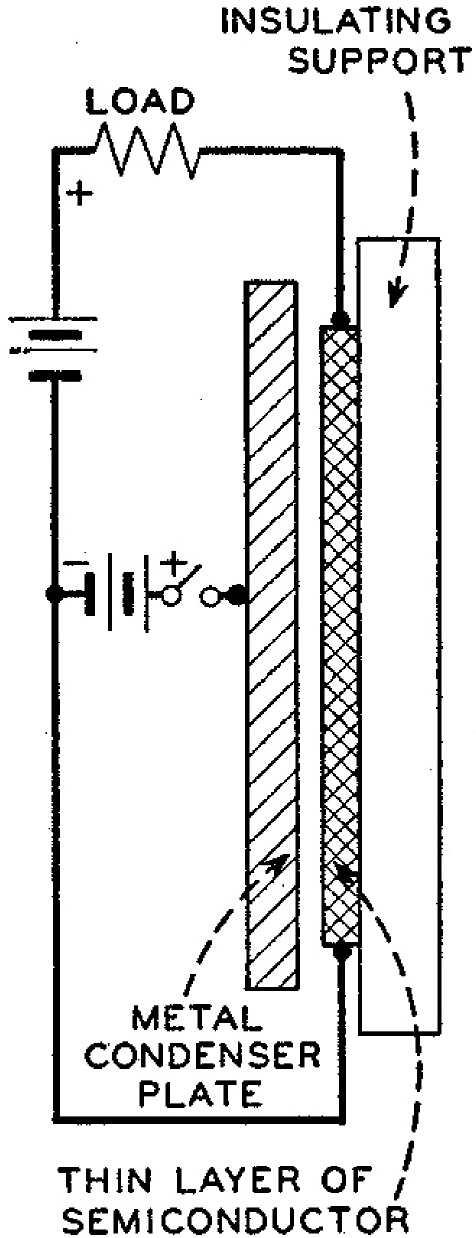
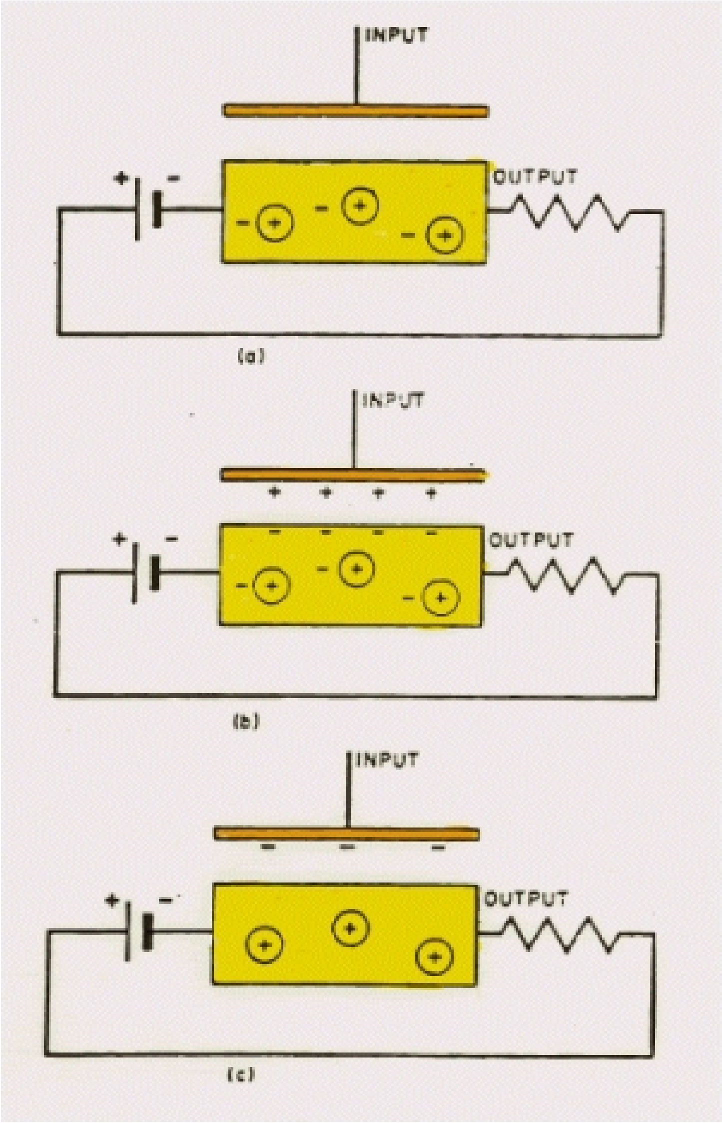
Shockley Field-Effect



After Shockley

Shockley Field-Effect (con't)



After Shockley

Field-Effect

- **Modulation of surface conductance by electrostatic induction**
  - Change ≈ 10% expected by classical electrostatics assuming induced majority carriers possessed mobility equal to bulk majority carriers
    - ***Spring '45***: Field-effect concept tested ⇒ "no" observable effect (evaporation of silicon, Teal/Shockley)
    - ***Fall '47***: field-effect concept tested ⇒ "some" observable effect (evaporation of high back-voltage Ge, Gibney/Pearson)
- ***Jun 23 '45*****: Shockley quantitative estimate of thin-layer field-effect experiment failure confirmed two weeks later by Bardeen**
- ***Mar 19 '46*****: Bardeen proposed surface states to explain failure**
  - Surface states blocked external electric field, shielding semiconductor interior from being probed
  - Field effect discrepancy interpreted as due to Bardeen's surface states
  - Shockley described Bardeen's hypothesis "one of the most significant research ideas of the semiconductor program"
- **Proof of principle to achieve solid-state amplifier device**

Bardeen's Surface-State Hypothesis

continued March 19, 1946

The experiment will give a negative result if a surface charge is built up ~~with~~ on the semi-conductor with such rapidity that the cross field is unable to penetrate the semi-conductor for an appreciable length of time. The field can not penetrate for 10^{-5} or 10^{-6} cm. as is assumed for the theory of rectification. We therefore have the following dilemma:

(a) If there are surface states which prevent penetration of field into the semi-conductor, they must be taken into account in the theory of rectification. Present theories which neglect such states give a reasonable good picture of rectification. In particular, the dependence of rectification on the work function of the metal seems to rule out a double layer at the ~~bounda~~ junction, as there is between two metals.

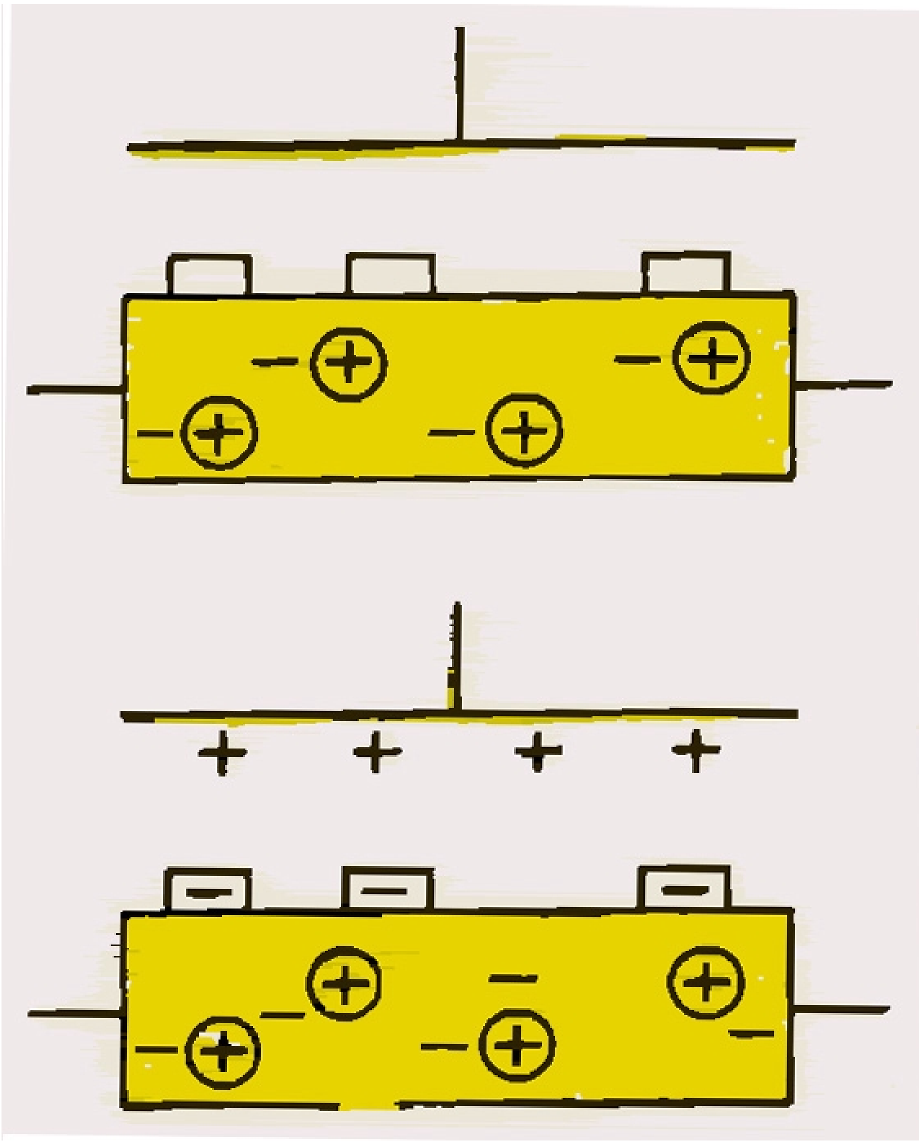
(b) If there are no surface states, the field should penetrate to sufficient depth to give a positive result for Shockley's experiment.

The negative result, especially if verified by further tests, seems to point to surface states. Can these be reconciled with rectification?

The following ideas were arrived at in part by discussions with Shockley on the afternoon of March 18 and the morning of March 19.

After Bardeen

Bardeen's Surface-State Hypothesis (con't)



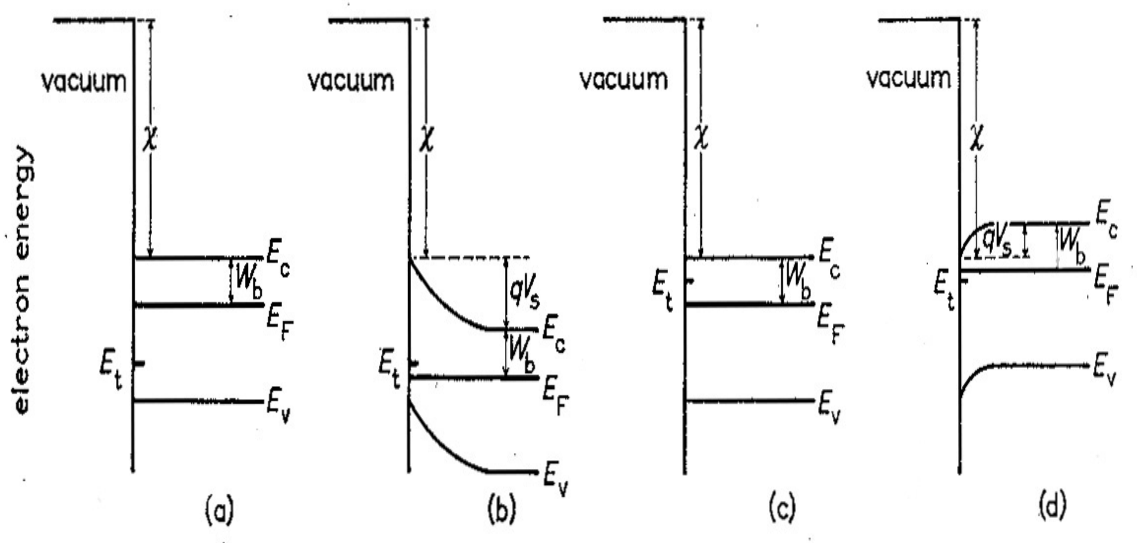
After Shockley

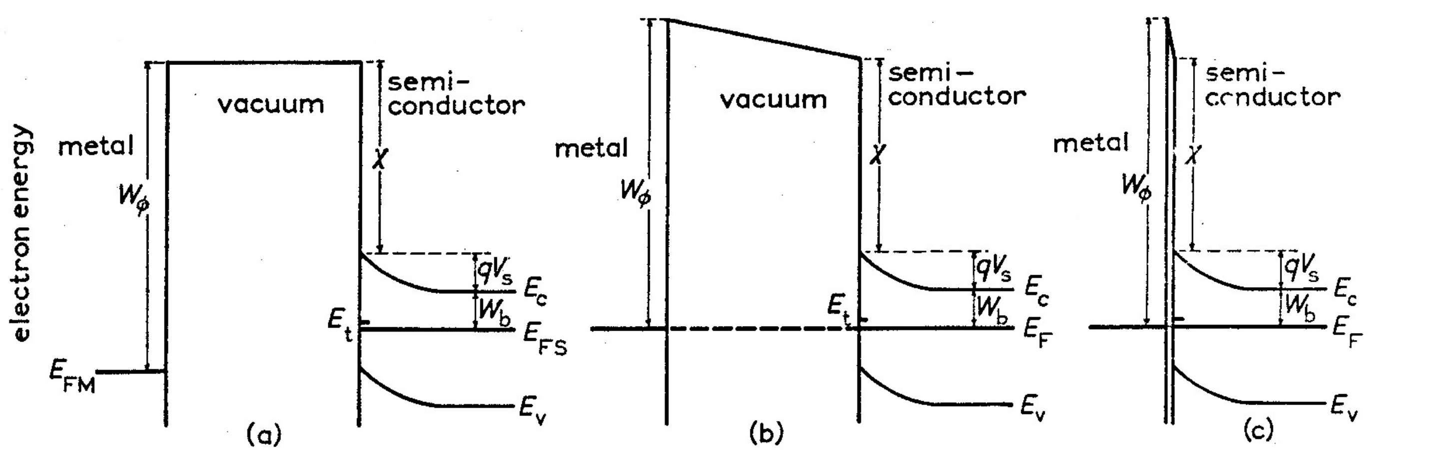
Surface States

- **Bardeen hypothesized qV_s independent of W_ϕ**
  - Result of thermodynamic requirement of charging localized trapping levels, N_T, (i.e., surface states) distributed in energy gap at semiconductor surface with simultaneous formation of SSCR of equal and opposite charge
  - Surface dipole formed, 2-D surface state charge and 3-D *SCCR*

- **Charge exchange between two solids due to difference in W_ϕ accomodated almost entirely by small change in occupancy of surface states, with minimal change in qV_s and *SSCR***
  - $N_T \sim 10^{12}/\mathrm{cm}^2$, $qV_{\phi s} \neq f\,(W_{\phi s}, W_{\phi m}\ and\ E_{fm})$
  - Main effect of metal contact is to supply current

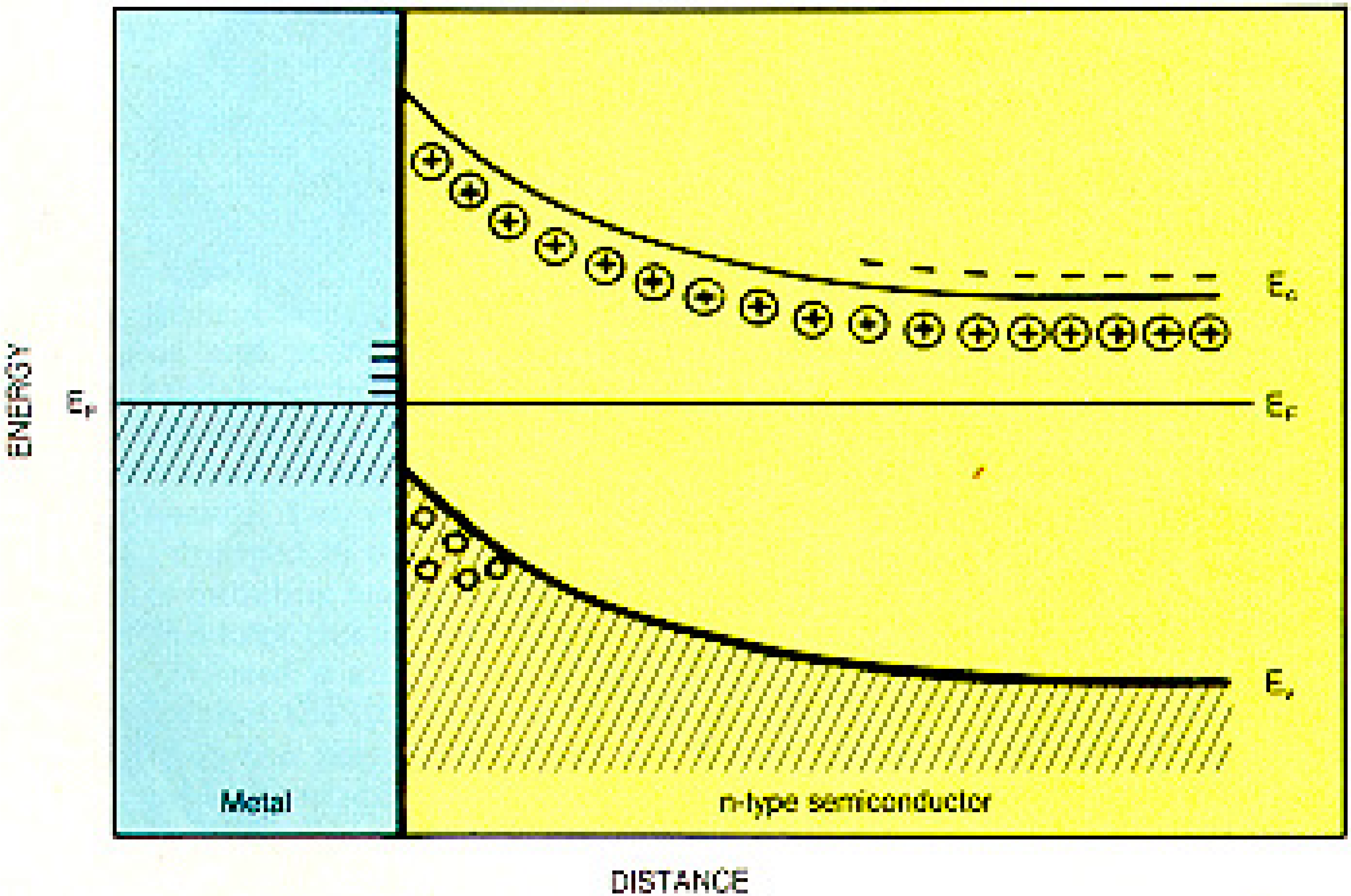
Energy -Level Diagram For N-Type Semiconductor With Surface States





After Many, Goldstein and Grover

Energy -Level Diagram For Metal / N-Type Semiconductor With Surface States



After Holonyak

Bardeen's Surface States

- **Confirmed by:**
  - Contact potential (c.p.) measurements
  - Change in c.p. upon exposure to illumination
  - Photoelectric emission
  - Shockley's field-effect experiment
- **Explained:**
  - Origin and concept of SSCR due to surface states
  - Practical independence of rectification characteristics with type of metal contact
  - Observed rectification characteristic between Ge-Ge contacts
  - Lack of significant modulation of surface conductance in field-effect experiment
  - Substantiated theoretical expectations that surface states were expected based on quantum mechanics

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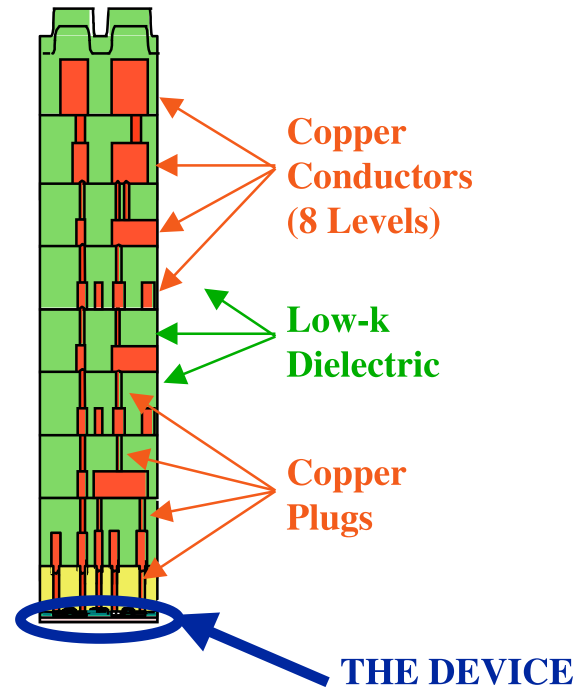

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Minority Carriers: ($n\ p = n_i^2$)

- **Band-bending near semiconductor surface due to spatially fixed, ionized dopants unshielded by majority carriers (described by Poisson's eq.)**
  - Band bending beyond depletion results in formation of inversion layer
  - Depletion layer ~ 1 µm, inversion layer several tens of nm

- **Free carriers in inversion layer designated as minority carriers**
  - Designation relative to (bulk) majority carriers generated from fixed, ionized dopant species uniformly distributed throughout sample volume (including inversion layer)
  - Minority carriers in inversion layer dominant source of free carriers

- **Sources of inversion layer**
  - **Sufficiently high density of intrinsic surface states**
  - **Sufficiently high density of adsorbed chemical species resulting in extrinsic surface states**
  - **Capacitively applied electric field**

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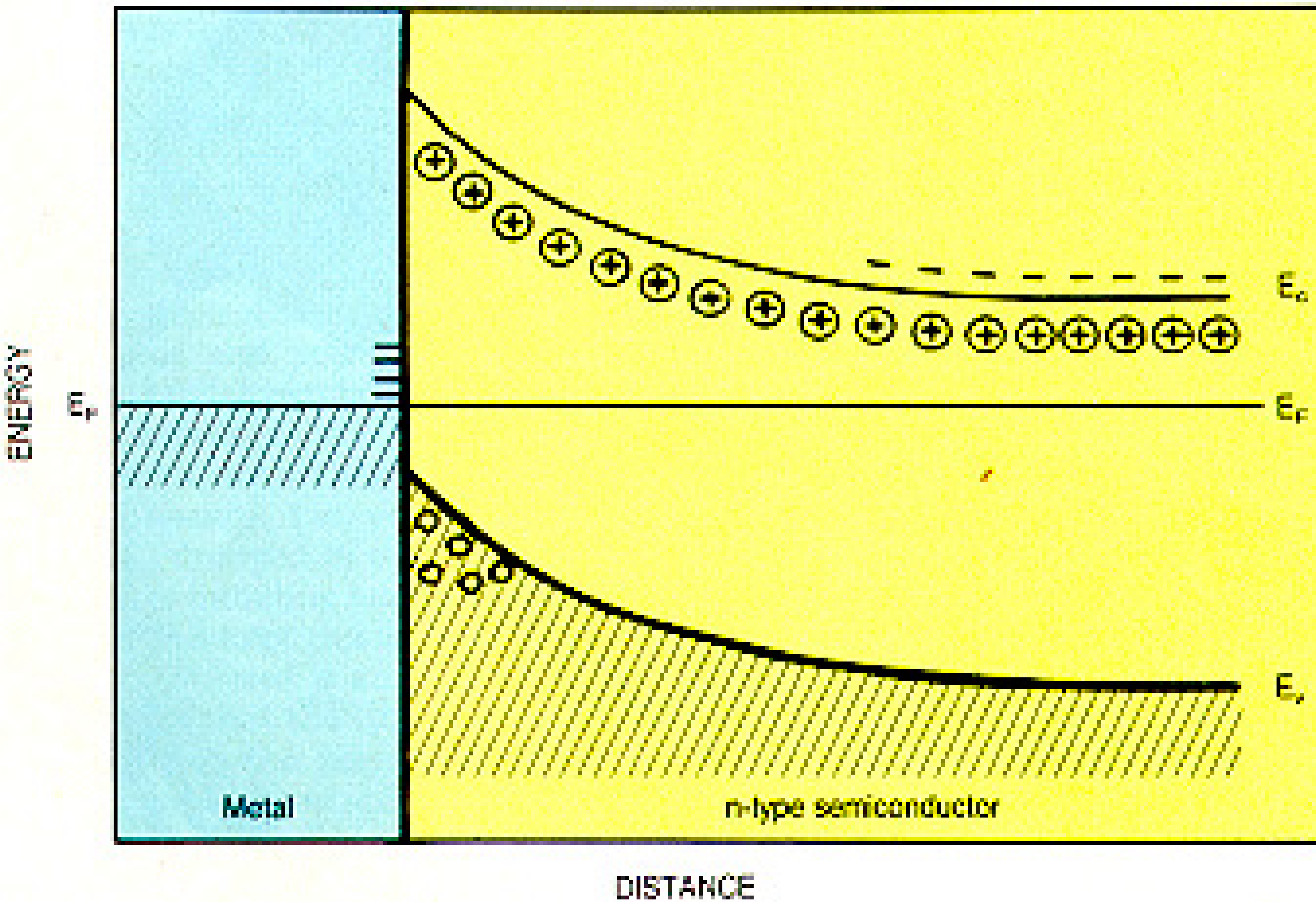

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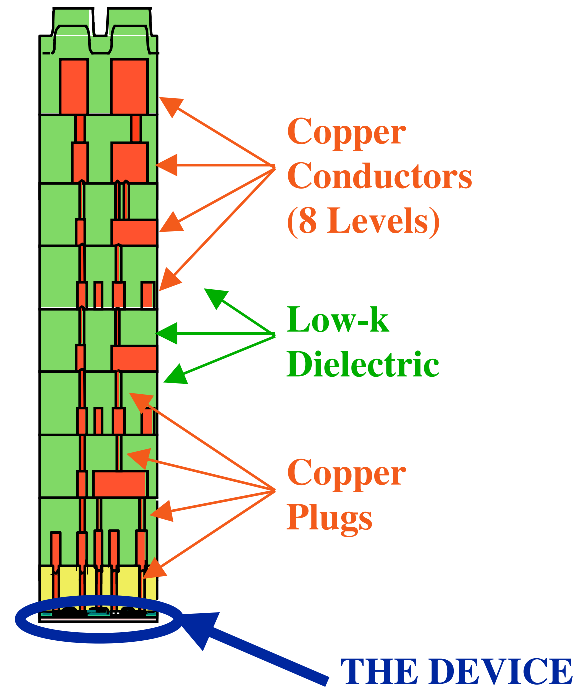

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Point-Contact Semiconductor Amplifier

- **Bardeen and Brattain's research to obviate influence of surface states in development of solid-state amplifier led to**
  - Invention of point-contact semiconductor amplifier
  - Observation of transistor action
  - Concept of minority-carrier transport
- **Point-contact semiconductor amplifier first device *based on minority carriers* introduced by current rather than optical or thermal techniques**

Surface-States Control

- *Apr '47*: **Brattain's exposure of silicon surface dipole layer to illumination induces charge on surface (due to internal electric field at surface driving free-carriers in opposite directions) resulting in change in c.p. ~ 0.1 V in liquid nitrogen**
  - Similar to Ohl's silicon p-n junction photovoltaic effect in '40
  - Brattain and Shockley deduced ≈ $10^{14}/cm^2$ surface states, more than sufficient to block external electric field
- *Nov 17, '47*: **Vibrating electrode placed in ethyl alcohol, acetone and toluene (and finally distilled water) at room temperature**
  - Contact potential changed by ~ 1 V on **p-type** sample in distilled water
- *Nov 17, '47*: **Gibney's suggestion to vary d.c. potential on vibrating electrode overcame surface state limitation**
- **Change in polarity of voltage (+) increased or (-) decreased change in contact potential induced by photovoltaic effect**
  - Positive or negative ions in electrolyte of distilled water migrated to p-type silicon's surface for (+) and (-) voltage polarity, respectively, where they neutralized surface states (+ polarity) and enhanced or reduced internal electric field at semiconductor surface, respectively

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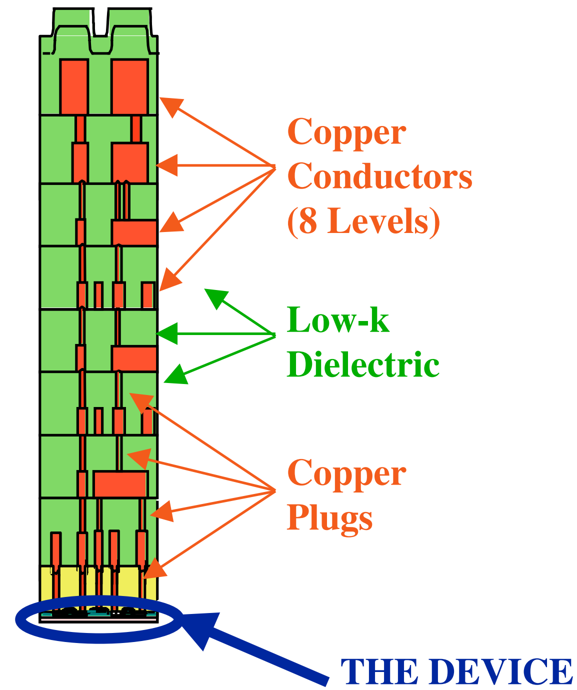

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Magic Month: Nov 17 '47 - Dec 16, '47

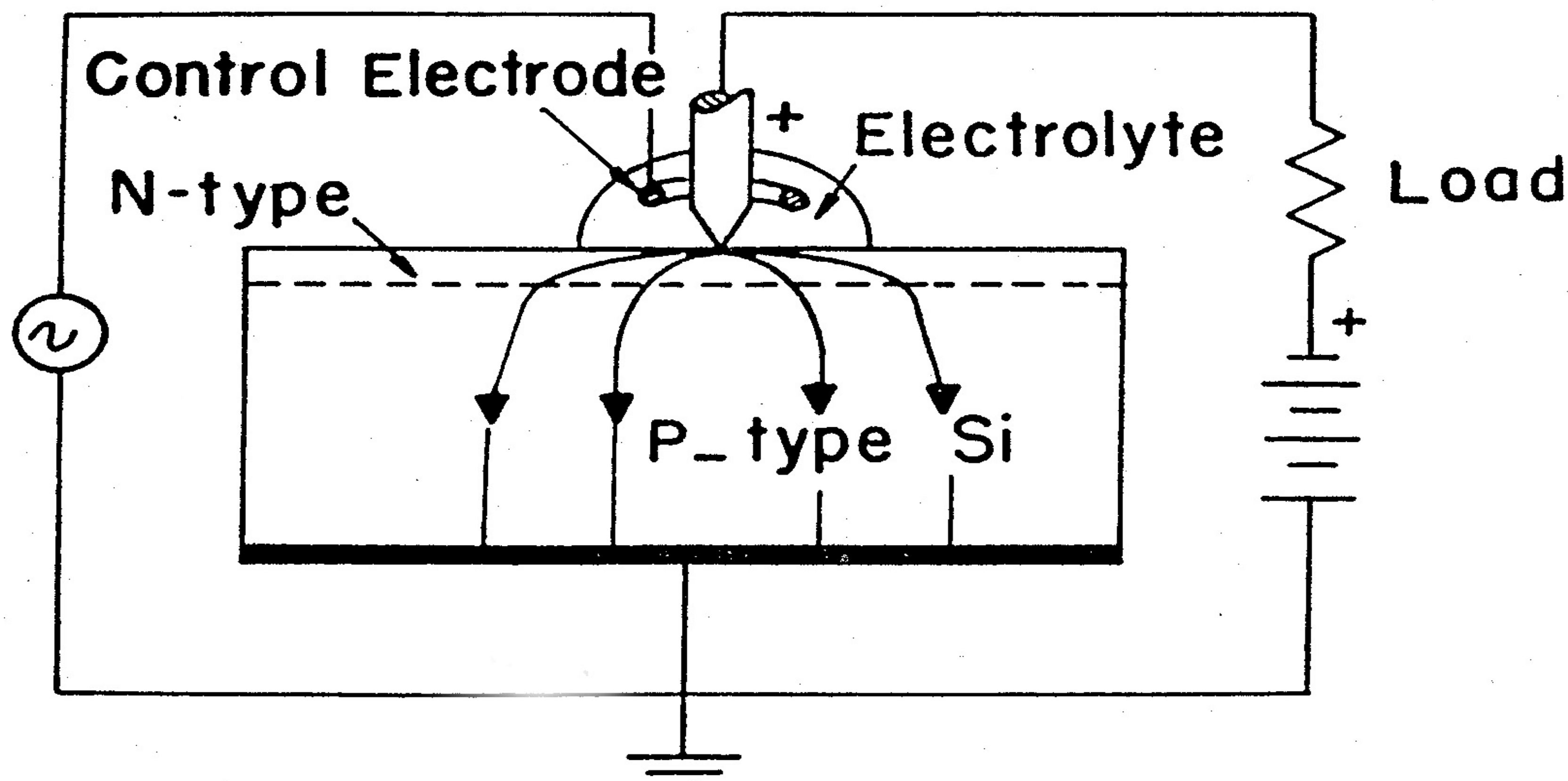
- **Surface states could be *neutralized***

Key concepts of inversion layer and field-effect principle were now able to be exploited

- ***Nov 20 '47*: Conception of Brattain and Gibney's *"034" patent* disclosure proposed amplifier via field effect with electrolyte to obtain high electric field**
  - "It is of course evident that the liquid dielectric could be replaced by a solid dielectric if one can be found having the proper ionic mobility to form such a dipole layer at the surface of semiconductor"
- ***Nov 23 '47*: Conception of Bardeen's *"033"patent* disclosure**
  - Utilization of inversion layer in conjunction with ***"034" patent***
  - Insulated point-contact probe

First Solid-State Amplifier

- ***Nov 21 '47*: Bardeen's circuit configuration combined electrolytic control (neutralization) of surface states to manipulate current flowing into point contact using CVD (polycrystalline Si) sample**
  - Slight (10%) current and power amplification achieved
  - Explicitly demonstrated validity of field-effect principle



Bardeen Archives / Holonyak

Magic Month: Nov 17 '47 - Dec 16, '47

DATE (1947)	DIELECTRIC MATERIAL	SEMI-CONDUCTOR MATERIAL	INVERSION LAYER FORMATION	AMPLIFICATION			FREQ. RANGE	BIAS	
				VOLTAGE	CURRENT	POWER	(cycles)	ELECTRODE CONTACT	POINT CONTACT
21-Nov	DISTILLED H_2O	P-TYPE SILICON	CHEMICAL	NO	YES	YES	< 10	(+)	(+)
08-Dec	GU	N-TYPE GERMANIUM (HIGH BACK-VOLTAGE)	ELECTRICAL	YES	NO	YES	< 10	(-)	(-)
10-Dec	GU	N-TYPE GERMANIUM (HIGH BACK-VOLTAGE)	CHEMICAL	YES	YES	YES	< 10	(-)	(-)
15-Dec	"GeO_2"	N-TYPE GERMANIUM (HIGH BACK-VOLTAGE)	CHEMICAL	YES	NO	NO	$10 - 10^4$	(+)	(-)
16-Dec	NONE	N-TYPE GERMANIUM (HIGH BACK-VOLTAGE)	CHEMICAL	YES	YES	YES	$10 - 10^4$	(+)	(-)

Magic Month: Nov 17 ‘47 - Dec 16, ‘47

- ***Nov 23 ‘47*: Conception of Bardeen’s *“033”patent* disclosure**
  - *Nov 22 ‘47*: “As noted by Brattain and Gibney [“034” patent] …. It occurred to the writer that the effect [semiconductor amplification] might be observed in the thin n-type layer on the surface of a block of p-type Si. It was suggested that this be tried because [CVD] thin films so far developed did not exhibit normal rectifying characteristics.”
    - Insulating gate modulating n-type inversion layer via field effect
    - Inversion layer confines minority-carrier transport, in series with reverse-biased n-p junction
    - Dec 8 ‘47 formed inversion layer electrically rather than chemically
  - Described by Shockley (1973) as “an insulated gate field effect transistor (IGFET) with an inversion layer channel”
    - Re-canted by Shockley (1976) since patent referred to Gibney’s ***“792” patent*** for preparing inversion layer on bulk semiconductor, rather than dynamically inducing inversion layer by gate voltage
  - Sah (1985) described device as sourceless MOS transistor

Five Transistor Device Patents Filed Before Public Announcement on June 30, 1948

No.	Invention	Conception	Reduction to Practice	Patent Dates		Inventors
				Filed	Issued [b]	
1…	Electrolyte F.E.T…………	20 Nov '47	21 Nov '47	26 Feb '48	3 Oct '50	WHB / RBG
2…	Inver. Layer IGFET……….	23 Nov '47	?	26 Feb '48	3 Oct '50	JB
3…	Elect-Form Inver. Layer…	Dec '47 ?	Dec '47 ?	26 Feb '48	17 Jul '51	RBG
4…	Point-Contact Transistor…	15 Dec '47	23 Dec '47	17 Jun '48 [a]	3 Oct '50	JB / WHB
5…	Junction Transistor………	23 Jan '48	Apr '50	26 Jun '48	25 Sep '51	WS

a. Originally filed 26 Feb '48; abandoned and refiled to include current gain at collector.

b. Patent numbers: 2,524,034; 2,524,033; 2,560,792; 2,524,035; 2,569,347.

After Shockley

Experimental Improvements I

- **Drop covered larger area than necessary requiring larger control currents than proper design would need**
  - ***Nov 24 '47*** (week of): Si ⇒ Ge, tungsten ⇒ Au and paraffin ⇒ Duco lacquer
  - ***Dec 4 '47***: Water ⇒ glycol borate ("gu") (water tended to evaporate, Moore)
  - Moore built circuit to allow easier variation of input signal's frequency
- **Two remaining obstacles**
  - Voltage amplification not observed
  - Frequency < 10 cycles
- ***Dec 4 '47*: Brattain summarized three device configurations**
  - Supports Nov 20th ("034") and Nov 23rd ("033") patent disclosures of modulating resistance of thin surface layer with voltage applied to electrolyte
  - Shockley's proposal to modulate p-n junction resistance with voltage applied to drop of electrolyte over junction
  - Anticipation of point-contact semiconductor amplifier ("035 patent)
    - ***"Two points close together the potential on one point to modulate the current flowing from the other point to the silicon"***

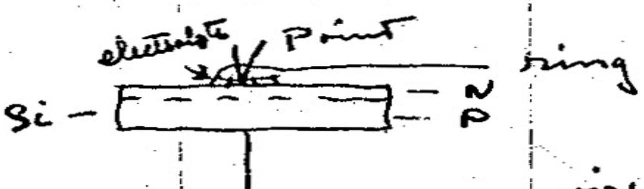
Brattain's Notebook Entry of December 4, 1947

Dec 4 1947

I was out due to a cold the experiment immediately above was taken over by Pearson. Any way the experiment worked N.B. 20912 page 75

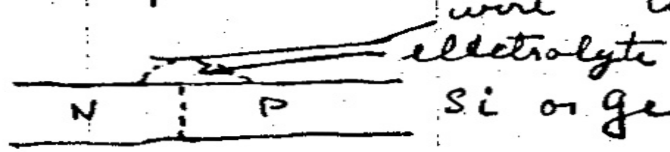
At a conference on Nov 22 or 29 it was decided that all the following combinations should be tried.

I



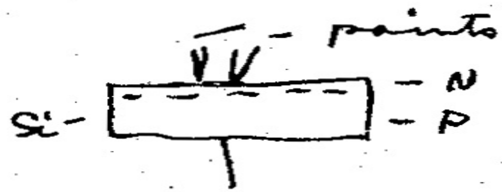
This is the one we have already tried and found to work

II



This is the one we tried on page 168

III



Two points close together the potential on one point to modulate the current flowing from the other point to the silicon

After Brattain

Magic Month: Nov 17 '47 - Dec 16, '47 (con't)

- ***Dec 8 '47*: Shockley described junction field-effect transistor and voltage gain using sufficiently reverse-biased p-n junction (with electrolyte over junction)**
  - Shockley described reverse bias effect at lunch with Bardeen and Brattain
  - Bardeen suggested use of high back-voltage Ge (perhaps also stimulated by Pearson's use of similar material on field-effect experiments)
- ***Dec 8 '47*: Bardeen and Brattain obtained voltage (2x) and power (330) gain using high back-voltage Ge and reverse bias**
  - Voltage / power amplification observed in Brattain's strongly depleted n-type sample with **negative** polarity on both control electrode and point contact
  - Interpreted as electrostatic induction of p-type inversion layer in n- type Ge sample $\Rightarrow$ holes flow to **negative** polarity point contact
- ***Dec 10 '47*: Repetition of experiment with different high back-voltage Ge sample chemically prepared with p-type inversion layer gave immense power (6000) and slight current (10%) gain**
  - Inversion layer exhibited higher electron mobility than CVD deposited film
  - Gibney noted thin film growth on Ge surface anodic oxide film growth due to large negative bias on control electrode

Magic Month: Nov 17 '47 - Dec 16, '47

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16-Dec	NONE	N-TYPE GERMANIUM (HIGH BACK-VOLTAGE)	CHEMICAL	YES	YES	YES	$10 - 10^4$	(+)	(-)

Magic Month: Nov 17 '47 - Dec 16, '47 (con't)

DATE Dec 8 1947
CASE NO. 38139-7

an external change of at least 1.0 volt across ~~2x10 ohms~~ giving thus a voltage amplification of 2 and a power amplification (9.3×10^{-5} watts out 1×10^{-7} watts in) 330

Walter H. Brattain
J. Bardeen

Note the above result or experiment was started as result of a luncheon discussion with Shockley and Bardeen and the final suggestion by Bardeen that voltage amplification could be obtained if the above experiment was performed on high back voltage Ge. The above sample was the only one available. It is not very high in back voltage but this will be tried as a limit going to higher back voltages

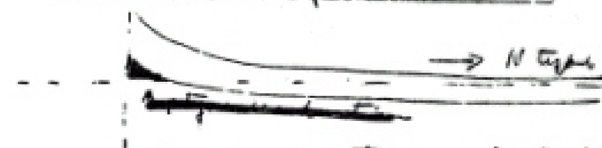
Walter H. Brattain

The reverse current and voltage at which the above change was obtained were 4.5 volts point + and 8×10^{-5} amp.

Bardeen suggests that the surface field is so strong that one

DATE Dec 8 1947
CASE NO. 38139-7

is actually getting P type conduction near the surface



and the negative potential on the grid is increasing this P type or hole conduction.

Walter H. Brattain

Dec 9 1947

Nothing has changed over night the same set up works. The voltage scale was expanded to test ratios at lower applied potentials

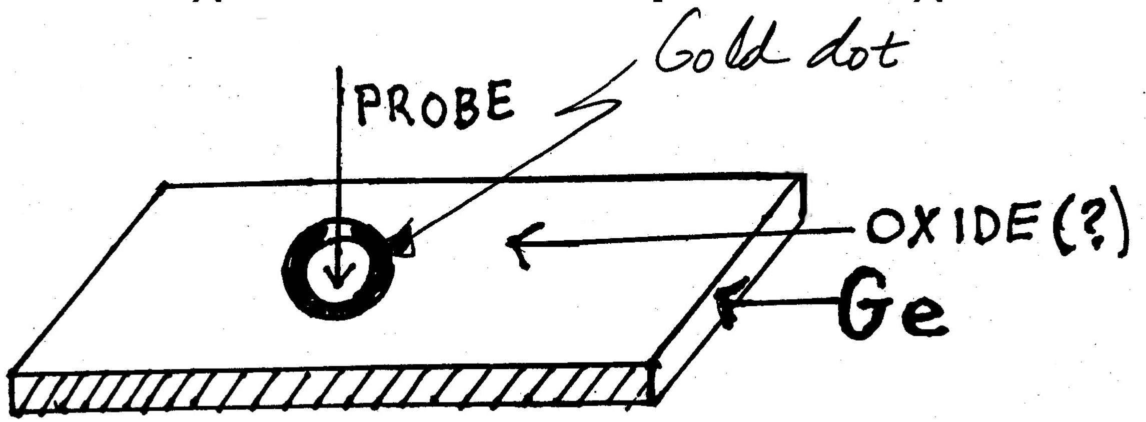
applied voltage 0.1 current 1×10^{-8}
output voltage 0.4 resistance 10^{5} ohms
applied power 1×10^{-9} watts
output power 1.6×10^{-6}

The electrolyte Si and ring act as a battery the optimum bias as far as sensitivity is concerned seems to be that bias that is equal and opposite to this internal cell.

This combination is also sensitive to light

Experimental Improvements II

- *Dec 12 '47*: **Replacement of electrolyte with thin insulating GeO_2 (to obtain higher frequency response and generate strong surface electric field) on different n-type Ge sample with p-type inversion layer and annular gold electrode expected to generate power gain**



- **Test failed with (-) voltage on both gold electrode / point contact; Brattain inadvertently shorted point contact / annular gold electrode**
  - Subsequent tests indicated GeO_2 washed off during sample preparation
- *Dec 15 '47*: **Test succeeded with gold electrode / point contact directly touching Ge surface with (+) voltage on gold electrode and (-) voltage on point contact placed adjacent (just outside) gold electrode**

Interpretation

- **Observed effect with (+) voltage on gold electrode and (-) voltage on point contact opposite to expected result if oxide present**
  - (+) voltage on gold electrode expected to electrostatically induce ***electrons*** in p-type inversion layer with ***decreased*** hole flow to (-) biased point contact
  - (-) voltage on gold electrode expected to electrostatically induce ***holes*** in p-type inversion layer with ***increased*** hole flow to (-) biased point contact

- **Gold electrode biased (+) emitted holes into p-type inversion layer which are collected by (-) biased point contact**
  - Signal applied between emitter and base electrode appeared in amplified across high resistance load between collector and base
    - Voltage gain (2x) observed independent of frequency (10 - 10^4 Hz)
  - ***First observation of semiconductor amplification (i.e., transistor effect)***
  - Bardeen suggested power gain if two narrow contacts spaced few mils apart

- ***Dec 15 '47*: Conception of Bardeen and Brattain's *"035" patent* disclosure on point-contact semiconductor amplifier**

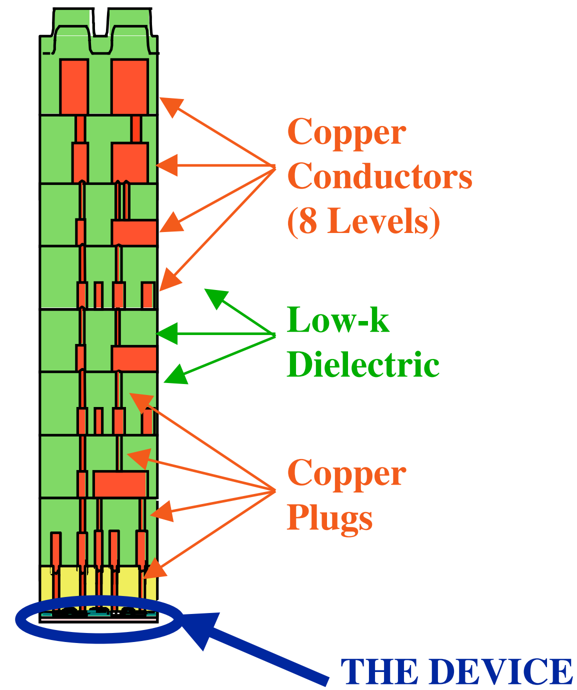
Magic Month: Nov 17 '47 - Dec 16, '47

DATE (1947)	DIELECTRIC MATERIAL	SEMI-CONDUCTOR MATERIAL	INVERSION LAYER FORMATION	AMPLIFICATION			FREQ. RANGE	BIAS	
				VOLTAGE	CURRENT	POWER	(cycles)	ELECTRODE CONTACT	POINT CONTACT
21-Nov	DISTILLED H_2O	P-TYPE SILICON	CHEMICAL	NO	YES	YES	< 10	(+)	(+)
08-Dec	GU	N-TYPE GERMANIUM (HIGH BACK-VOLTAGE)	ELECTRICAL	YES	NO	YES	< 10	(-)	(-)
10-Dec	GU	N-TYPE GERMANIUM (HIGH BACK-VOLTAGE)	CHEMICAL	YES	YES	YES	< 10	(-)	(-)
15-Dec	"GeO_2"	N-TYPE GERMANIUM (HIGH BACK-VOLTAGE)	CHEMICAL	YES	NO	NO	$10 - 10^4$	(+)	(-)
16-Dec	NONE	N-TYPE GERMANIUM (HIGH BACK-VOLTAGE)	CHEMICAL	YES	YES	YES	$10 - 10^4$	(+)	(-)

Agenda

- **Introduction**
- **Schottky-barrier diode**
  - Rectification
- **Point-contact semiconductor amplifier**
  - Field effect / surface states
  - Minority carriers
  - Surface-states control
  - Magic month: Nov 17 ‘47 - Dec 16 ‘47
  - **Historic day- Dec 16 ‘47**
  - Recapitulation / Serendipity Factors
  - Naming invention / patents
- **Bipolar junction transistor**
  - Magic month: Dec 24 ‘47- Jan 23 ‘48
  - Implementation
- **Contemporaneous Events**
- **Modern silicon MOSFETs**
- **Summary**
- **Acknowledgements**

100 nm High End Microprocessor



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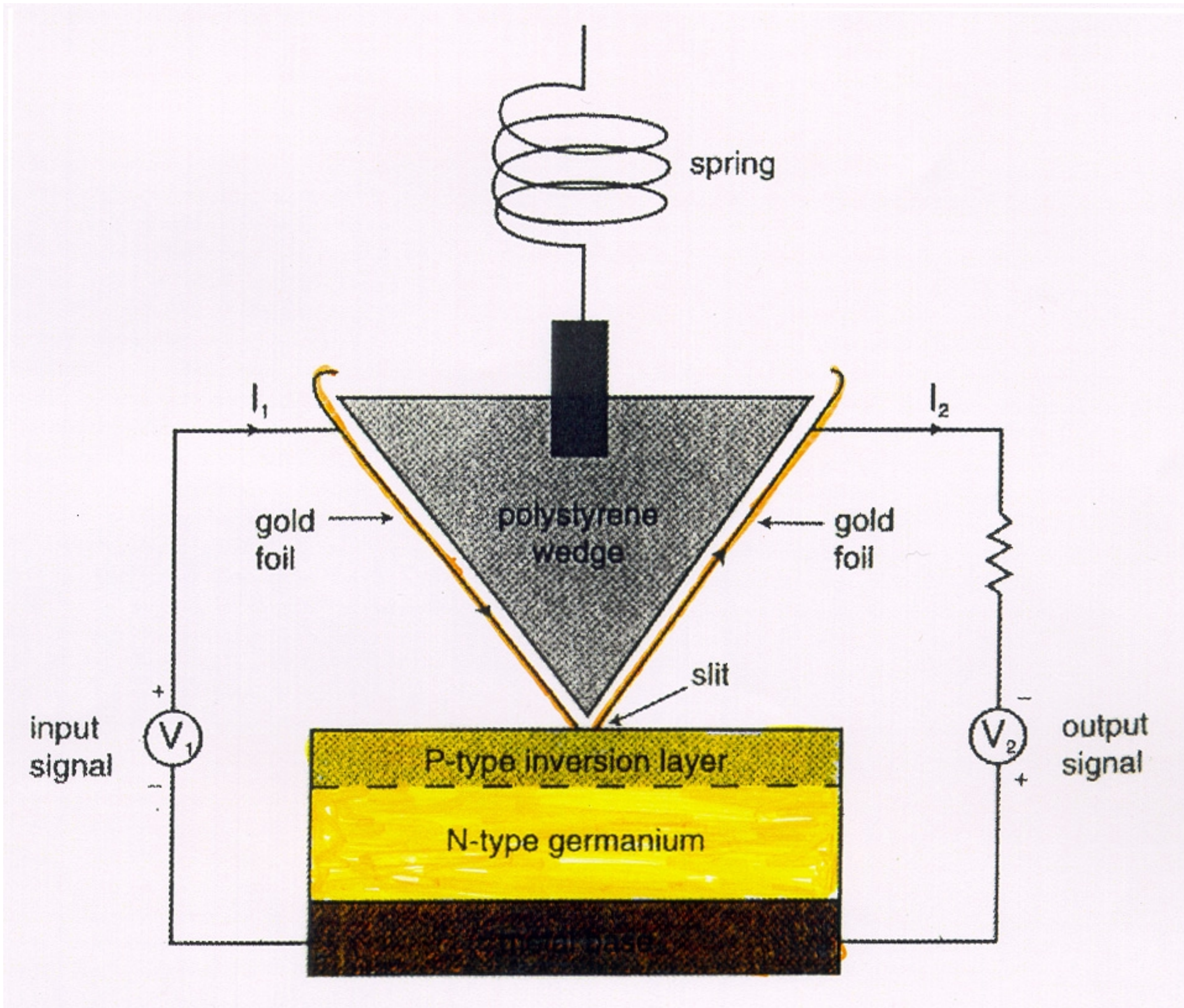
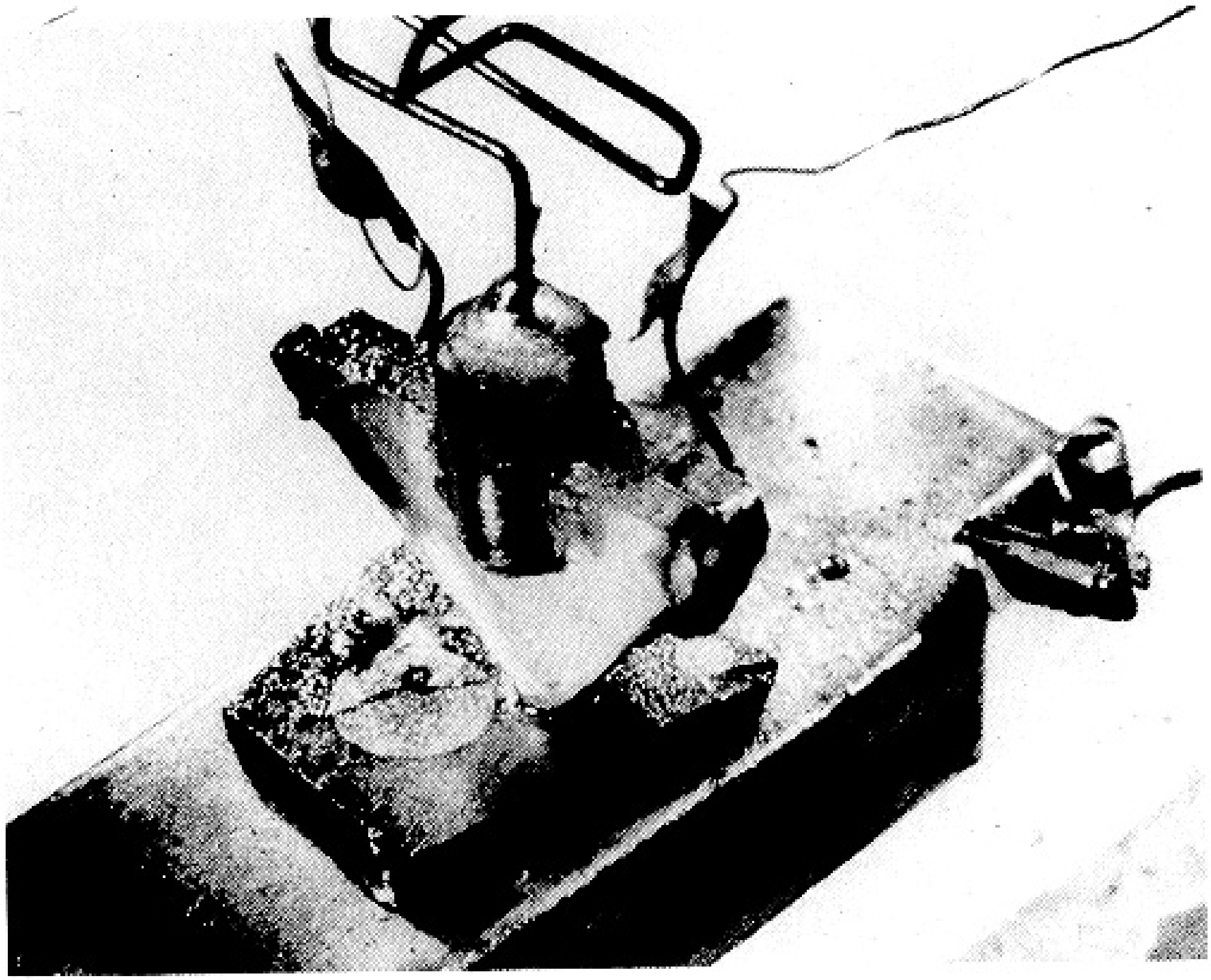
Historic Day: December 16, 1947



After Riordan

Historic Day: December 16, 1947 (con't)



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Magic Month: Nov 17 '47 - Dec 16, '47

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16-Dec	NONE	N-TYPE GERMANIUM (HIGH BACK-VOLTAGE)	CHEMICAL	YES	YES	YES	$10 - 10^4$	(+)	(-)

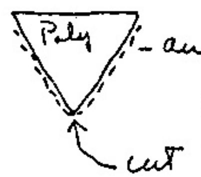
Historic Day: December 16, 1947 (con't)

- **Dec 16 '47: Brattain's notebook**
  - "Constructed a device to make two point contacts to Ge close together (Dreher constructed it). The device is as follows: a polystyrene wedge with gold tape cemented on the edge of the wedge. After the gold was cemented it was cut at the apex and the cut was filled with wax. Using this ***double point contact contact was made to*** a Ge surface that had been anodized to 90 volts, electrolyte washed off in H_2O [germanium oxide apparently also washed off] and then had some gold spots evaporated on it. The gold contacts were pressed down on the bare surface. Both gold contacts rectified nicely."
  - "The separation between points was about 4 x 10^{-3} cm. One point was used as a grid [control electrode] and the other point as a plate [collector]. The bias (D.C.) on the grid had to be ***positive*** to get amplification. Several cases were measured. …. Power gain 1.3, voltage gain 15 at a plate bias of about 15 V."
  - Another setting yielded voltage gain of 4 associated with a greater power gain of 4.5 implying current gain greater than 1.1 [Shockley notes current gain, important feature in obtaining power gain and simplifying circuit design, not mentioned in original Feb 26 '48 "035" patent, but incorporated in re-filing on Jun 17 '48, letting Feb 26 '48 version lapse]

Historic Day: December 16, 1947 (con't)

Dec 16 1947 Constructed a device to make two point contacts to Ge close together (Dreher constructed it) The device is as follows: a ~~pla~~ polystyrene wedge with gold tape cemented on the edge of the wedge

Sketch # BA 240026



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After Brattain

Historic Day: December 16, 1947 (con't)

- **Input impedance (at emitter) ~ 25 ohms**
- **Output impedance (at collector) ~ 10^4 - 10^5 ohms**
  - Matched to high impedance load
- **Emitter and collector currents similar in magnitude ⇒ power amplification of input signal at 15 MHz**
- **Subsequent experiments ⇒ power gain of 20 dB with 25 mW output at frequencies up to 10 MHz**

- **Bardeen and Brattain had amplified both power and current/voltage at audio frequencies about one month after Brattain and Gibney's Nov 17, '47 breakthrough**

⇓

Solid-State Amplifier

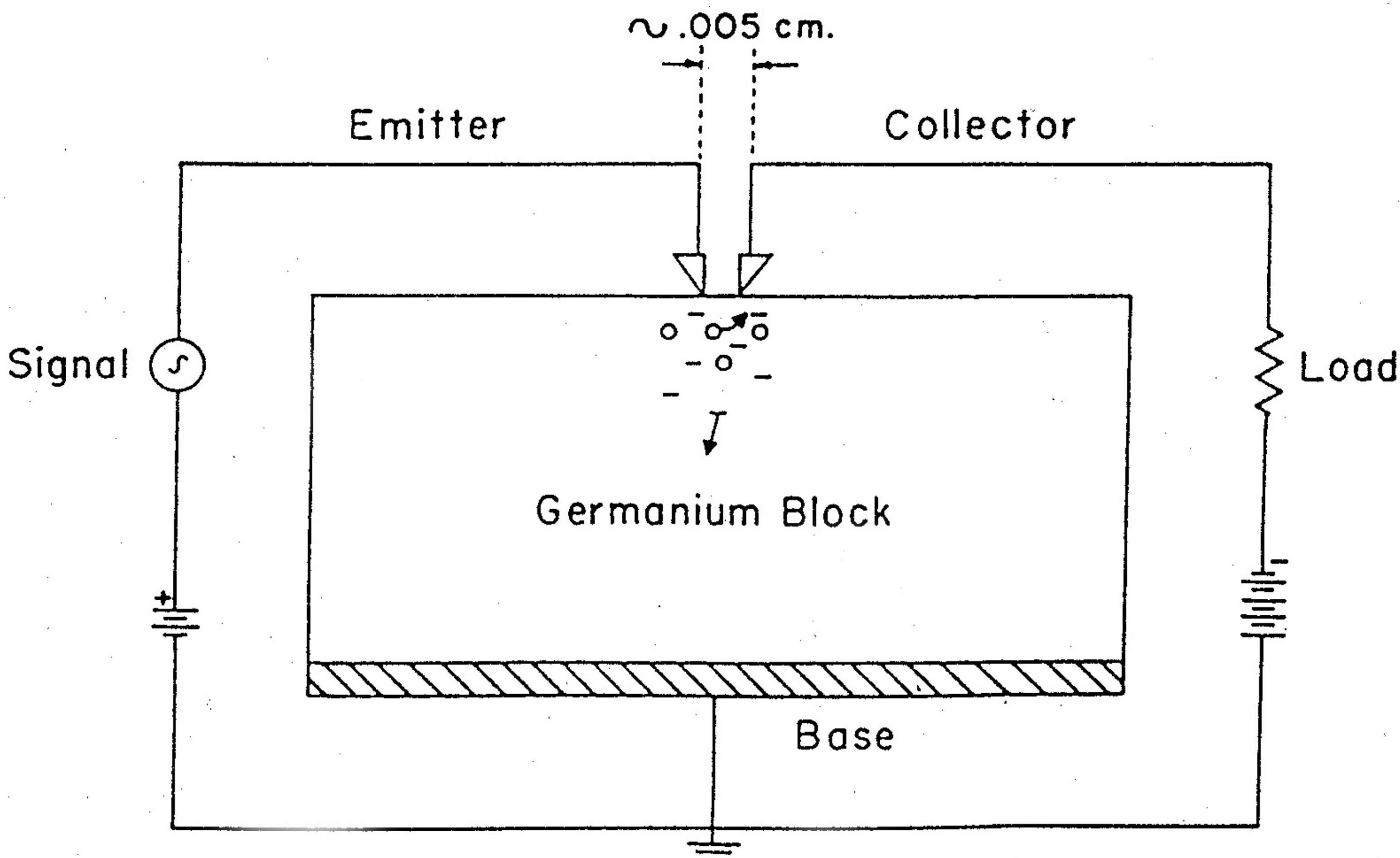
- **Point-contact semiconductor amplifier demonstrated to BTL's executives Dec 23 '47; Brattain's notebook entry Dec 24 '47 also included demonstration of oscillator behavior**

Presentation to BTL Executives - Dec 23, '47

After Brattain

Point-Contact Semiconductor Amplifier

- **First solid-state device utilizing *minority carriers introduced by current* rather than optical or thermal techniques**



Bardeen Archives / Holonyak

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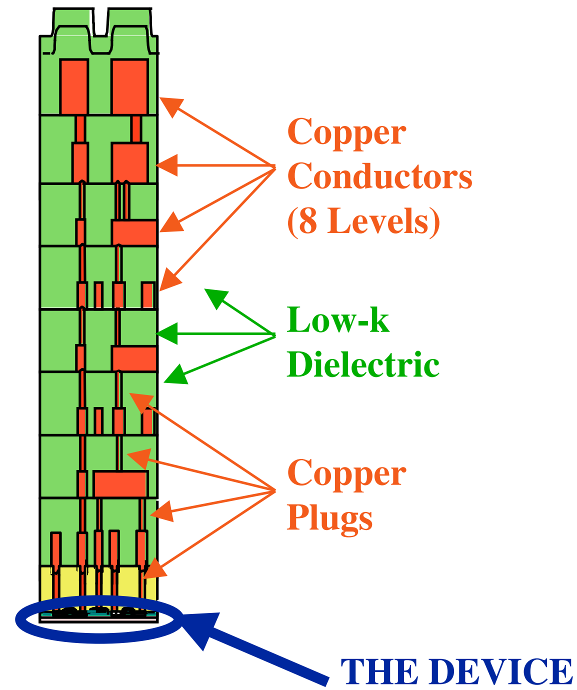
100 nm High End Microprocessor



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Recapitulation - Serendipity Factors

- **Solid-state amplifier invented by Bardeen and Brattain "completely different in principle and function from field-effect transistor proposed by Shockley [envisioned as majority carrier device] but served original desired function as triode amplifier"**
  - "Failure of Shockley's original field effect transistor device"
  - "Bardeen's focus on surface states and inversion layer unexpectedly generated point-contact transistor configuration"
  - "Switch from Si to Ge"
  - Utilization of two whiskers "close" together
  - Brattain's accidental destruction (in his mind) of GeO_2 film (subsequently realized not present)
- **"Results … obtained by admixture of accident, brilliant insight and luck …. The fact results were reverse of what they expected initially … namely that minority, rather than majority carriers, were modulated is irrelevant. Accident had favored their prepared minds! They were amply prepared to understand and exploit the breakthrough…."**
  - "Bardeen & Brattain's attentiveness to pick up implications of their invention"

Recapitulation - Serendipity Factors (con't)

- **Device introduced holes, minority carriers, into semiconductor, irrespective of spatial location of emitted (holes) carriers**
  - Three-dimensional device in which surface properties integral to operation

- **Issues clarified during next several years**
  - Forming
  - Implications of internal electric field at semiconductor surface
  - Quantitative expressions for surface electrical characteristics (*SSCR* and V_s)
  - Surface-states at low-temperature

Magic Month: Nov 17 '47 - Dec 16, '47

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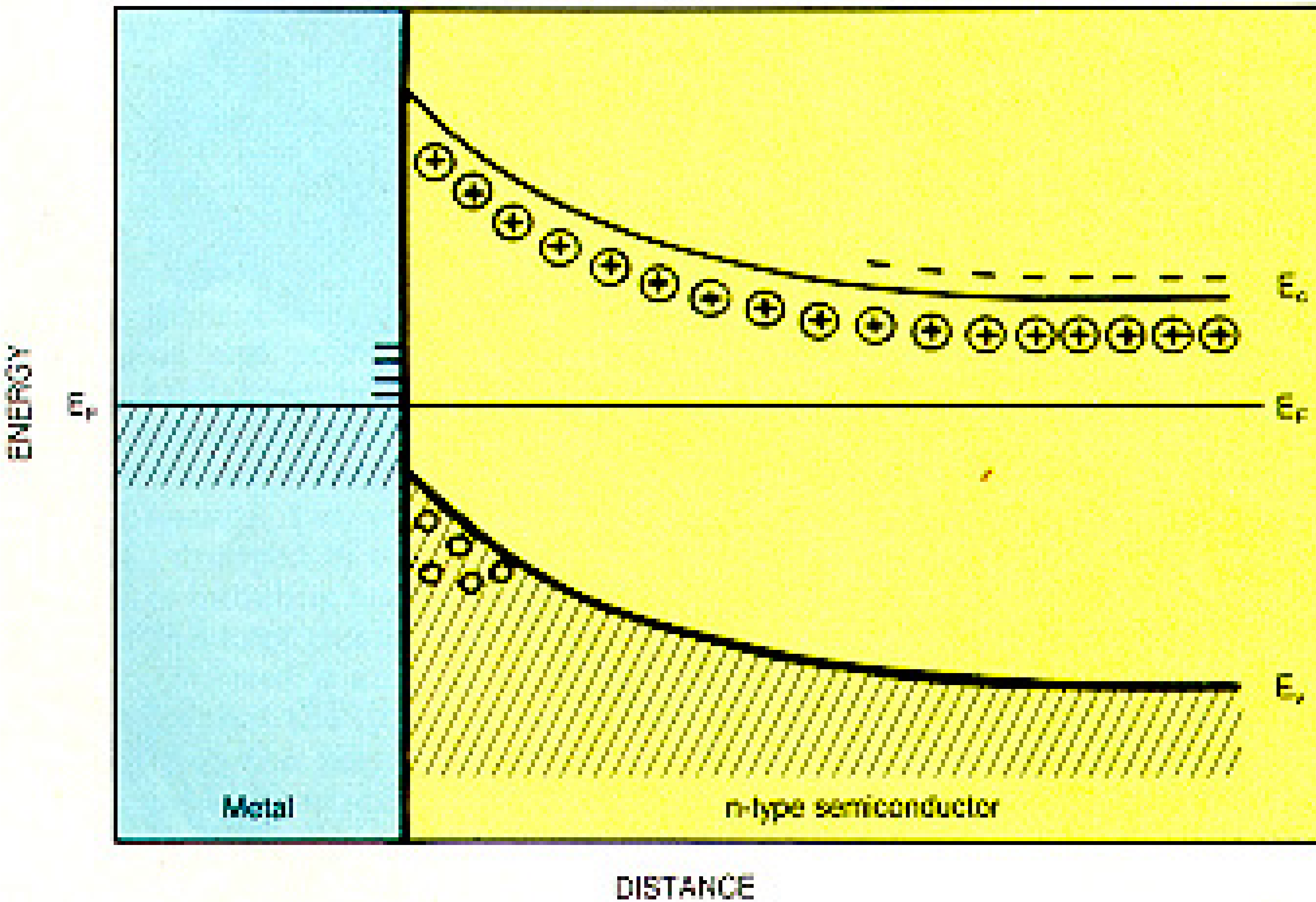
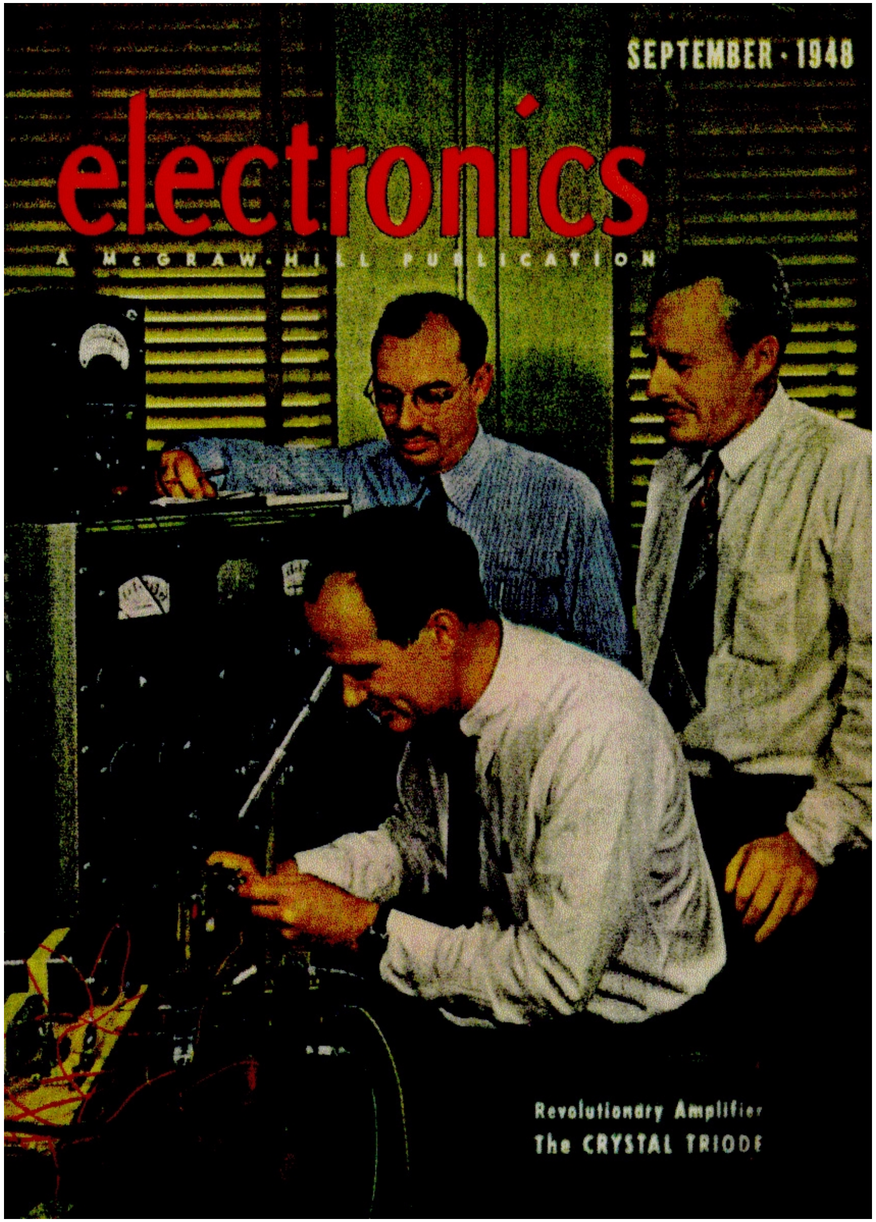
Energy -Level Diagram For Metal / N-Type Semiconductor With Surface States



After Holonyak

The Famous Picture



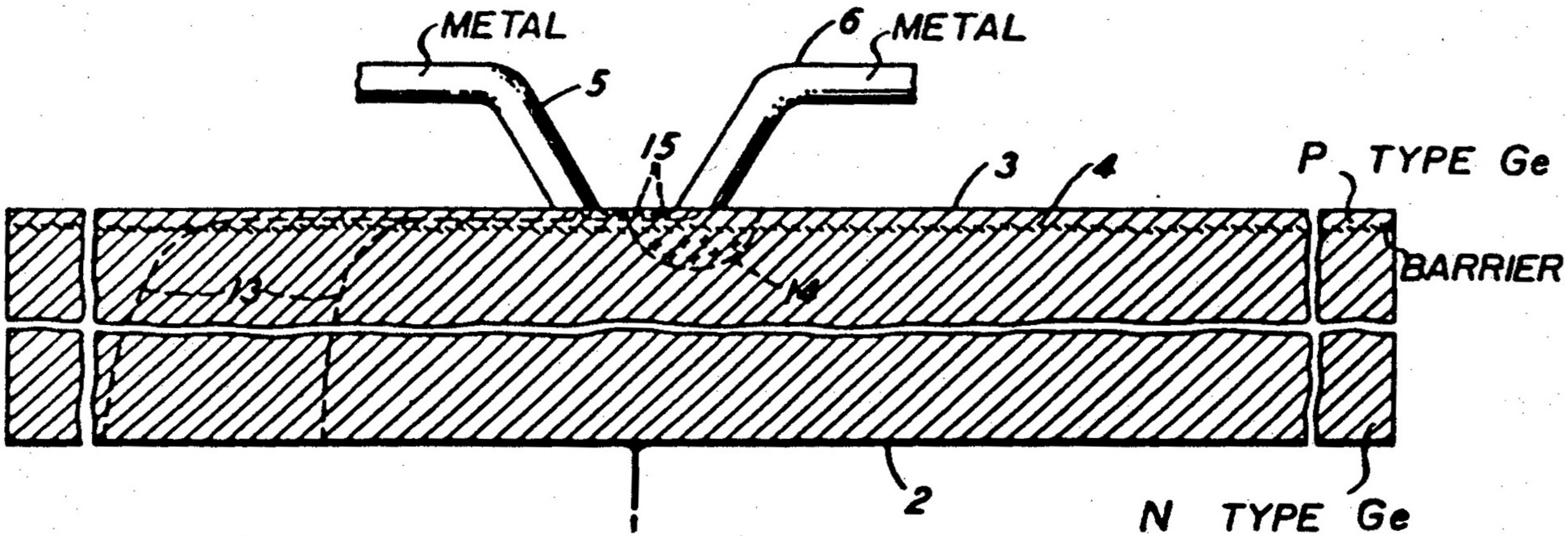
After Riordan

The Famous Picture (25 Years Later)

After Riordan

Hole Flow From Emitter to Collector

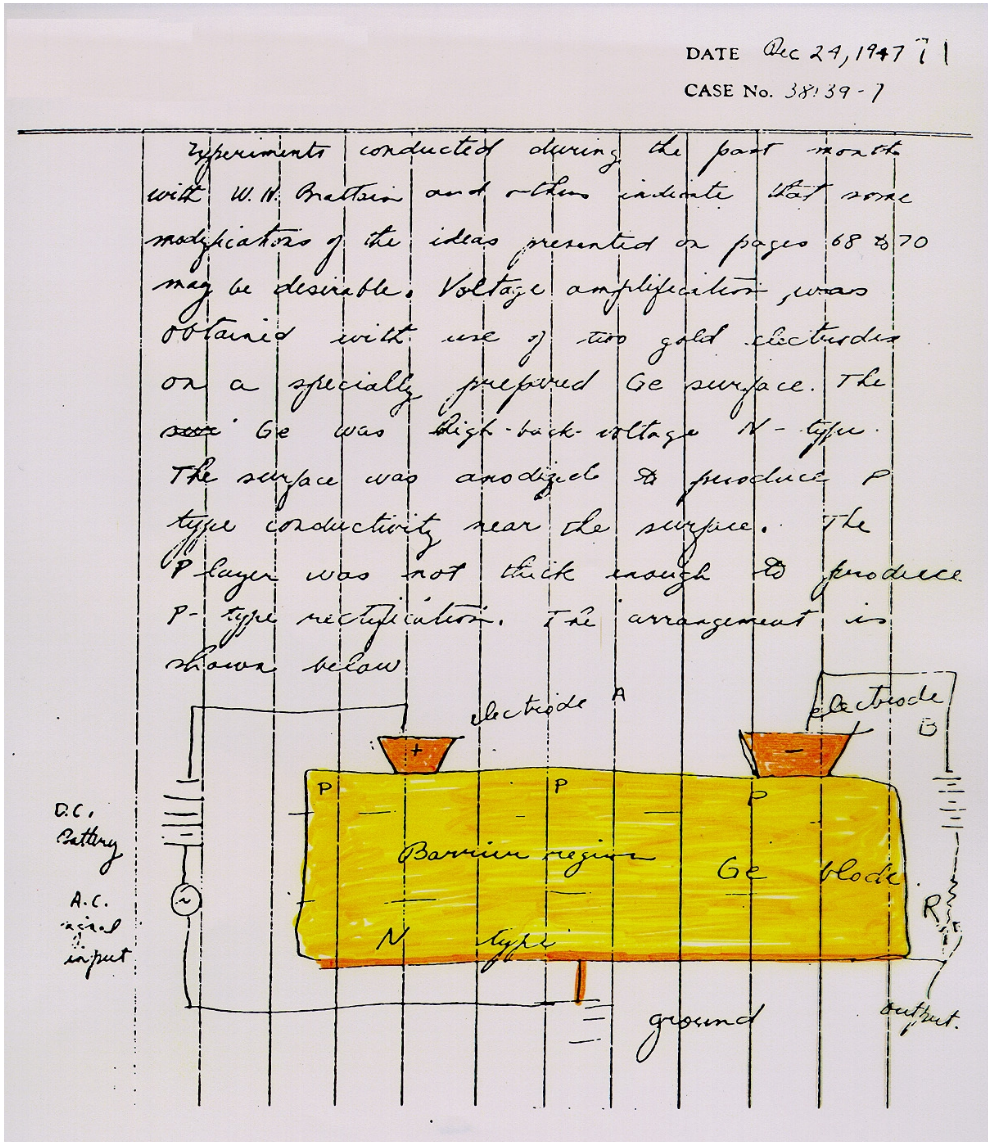
- **" A large part of the current in both the forward and reverse directions flows *via* [italics in original] the P-type conducting layer at the surface"**



- **While Bardeen and Brattain were cognizant of transport of holes into bulk, their geometrical structure favored transport of holes from emitter to collector via p-type inversion layer**

After 035 patent

Hole Flow From Emitter to Collector

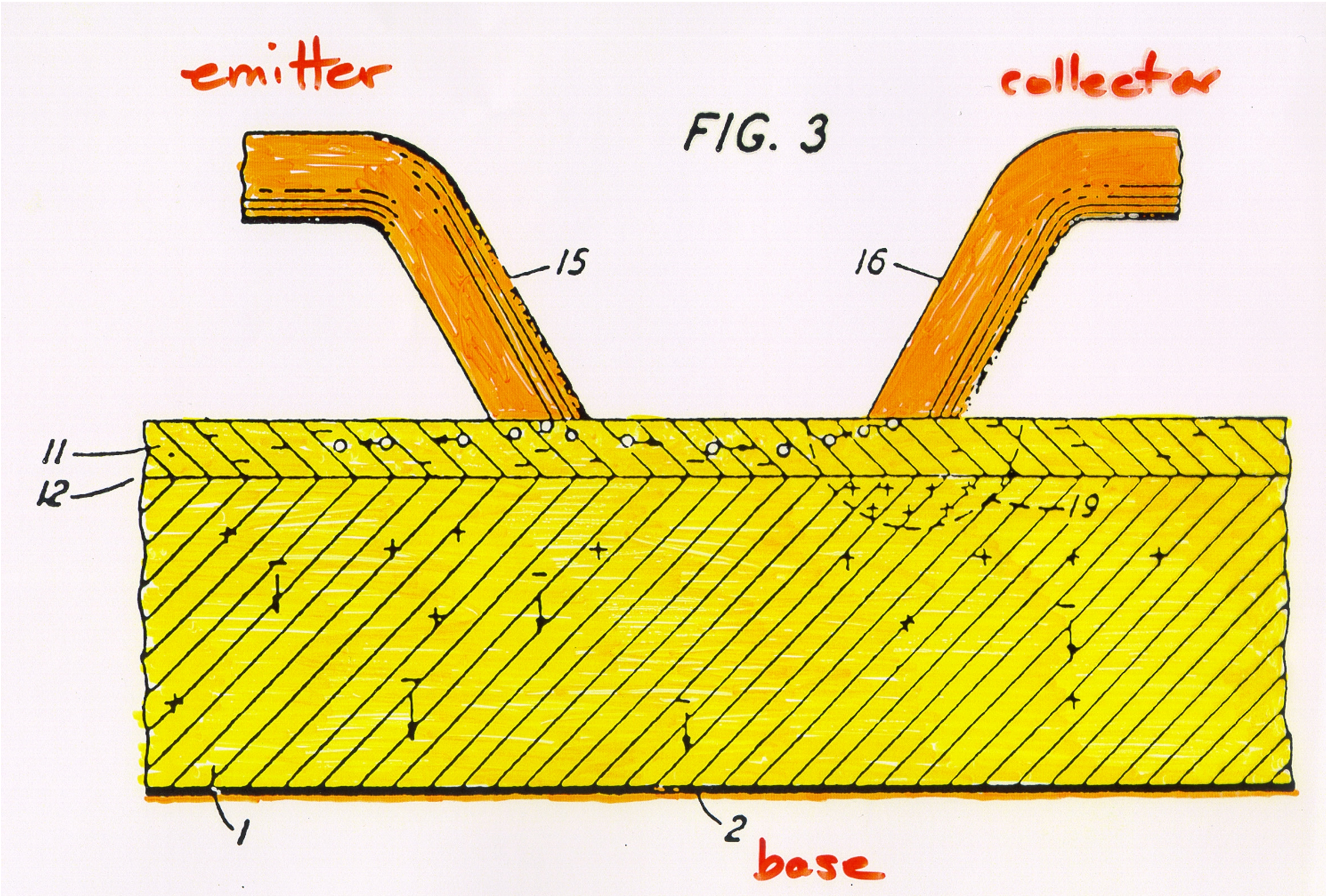


DATE Dec 24, 1947 71
CASE No. 38139-7

Experiments conducted during the past month with W. H. Brattain and others indicate that some modifications of the ideas presented on pages 68 & 70 may be desirable. Voltage amplification was obtained with use of two gold electrodes on a specially prepared Ge surface. The ~~sur~~ Ge was high-back-voltage N-type. The surface was anodized to produce P type conductivity near the surface. The P layer was not thick enough to produce P-type rectification. The arrangement is shown below

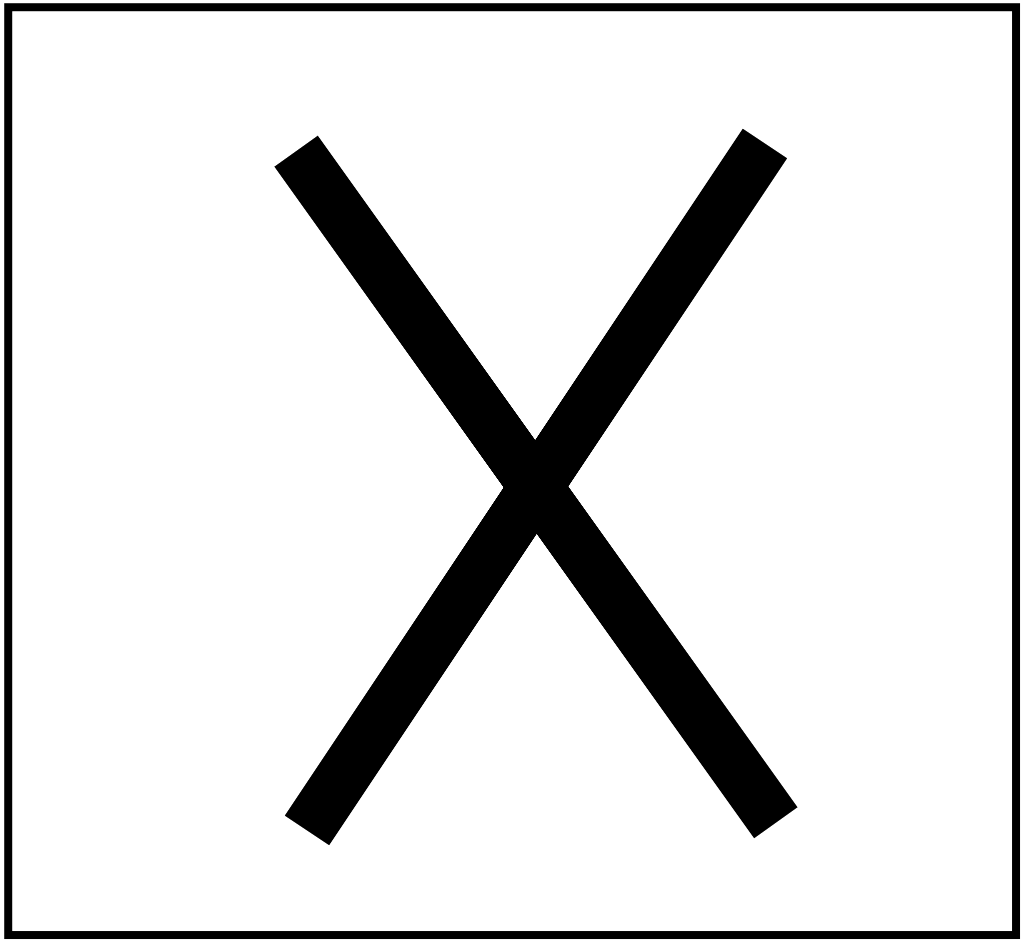
After Bardeen (courtesy Riordan)

Hole Flow From Emitter to Collector



After 792 patent

Hole Flow From Emitter to Collector



Bulk Transport Conjecture

- **Model calculation consistent with some fraction of bulk minority-carrier transport concurrent with transport via inversion layer**
  - $L = \sqrt{D_p \tau_p}$
  - $(D_p / \mu_p) = kT/q$
    - Taking $D_p = 49$ cm^2/s and $\tau_p \approx 10$ µs for n-type large-grained polycrystalline Ge (probes within grain) $\Rightarrow$
      - $L \approx 225$ µm, $\approx$ 5x probe spacing of 50 µm
    - Taking $D_p = 12$ cm^2/s and $\tau_p \approx 1$ µs for n-type polycrystalline Ge (probes in adjacent grains) $\Rightarrow$
      - $L \approx 35$ µm, $\approx$ 0.7x probe spacing of 50 µm
- **Speculation that Bardeen and Brattain's n-type bulk sample did not exhibit p-type surface inversion layer and exhibited bulk transport to much larger degree than indicated in '48 paper**
- **Shockley recalled a "most trying week somewhere in late Dec or early Jan when, for some reason the [surface] treatments failed and no transistors worked"**

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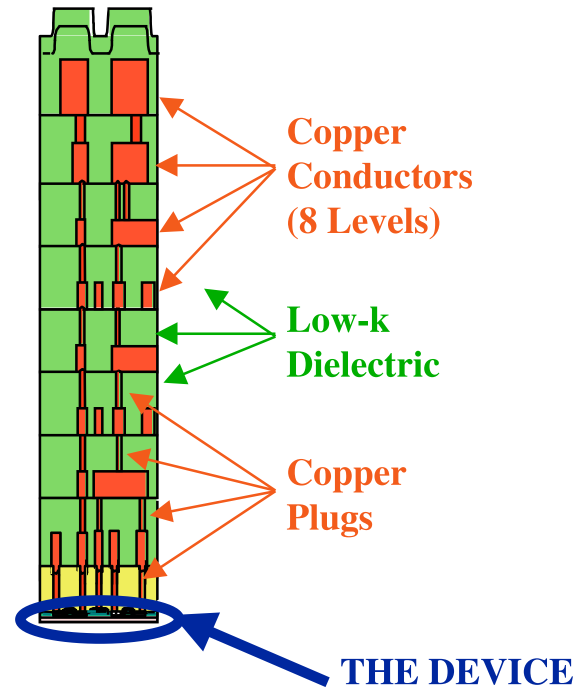
100 nm High End Microprocessor



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Naming The Invention

- **Pierce suggested *transistor* since electric field modulating resistance transverse to minority-carrier current**
- **Pierce apparently also noted point-contact transistor dual of vacuum tube from circuit point of view**
  - Therefore, electrical dual of transconductance, important parameter of vacuum tube, was transresistance, shortened to ***transistor***
  - A number of device names terminate in sequence "or" as conductor, resistor, varistor, thermistor
- **Another interpretation noted prefix "trans" designates translational property of device, while root "istor" classified it as solid circuit element**

Patents

- **Original patent application applied by BTL included Shockley's field-effect transistor, albeit effect was extremely small**
- **AT&T attorneys, however, found previous patents awarded for rather similar field-effect amplifiers to Lilienfeld (as early as 1930) and Heil**
  - Sah has noted neither Lilienfeld nor Heil recognized necessity of inversion layer for operation of their proposed devices
- **Shockley not included in point-contact patent application**
- **Severe disappointment became major impetus for spurring Shockley's subsequent seminal contributions**
  - Injection over barrier
  - P-n junction theory
  - P-n junction transistor

Five Transistor Device Patents Filed Before Public Announcement on June 30, 1948

No.	Invention	Conception	Reduction to Practice	Patent Dates		Inventors
				Filed	Issued [b]	
1…	Electrolyte F.E.T…………	20 Nov '47	21 Nov '47	26 Feb '48	3 Oct '50	WHB / RBG
2…	Inver. Layer IGFET………	23 Nov '47	?	26 Feb '48	3 Oct '50	JB
3…	Elect-Form Inver. Layer…	Dec '47 ?	Dec '47 ?	26 Feb '48	17 Jul '51	RBG
4…	Point-Contact Transistor…	15 Dec '47	23 Dec '47	17 Jun '48 [a]	3 Oct '50	JB / WHB
5…	Junction Transistor………	23 Jan '48	Apr '50	26 Jun '48	25 Sep '51	WS

a. Originally filed 26 Feb '48; abandoned and refiled to include current gain at collector.

b. Patent numbers: 2,524,034; 2,524,033; 2,560,792; 2,524,035; 2,569,347.

After Shockley

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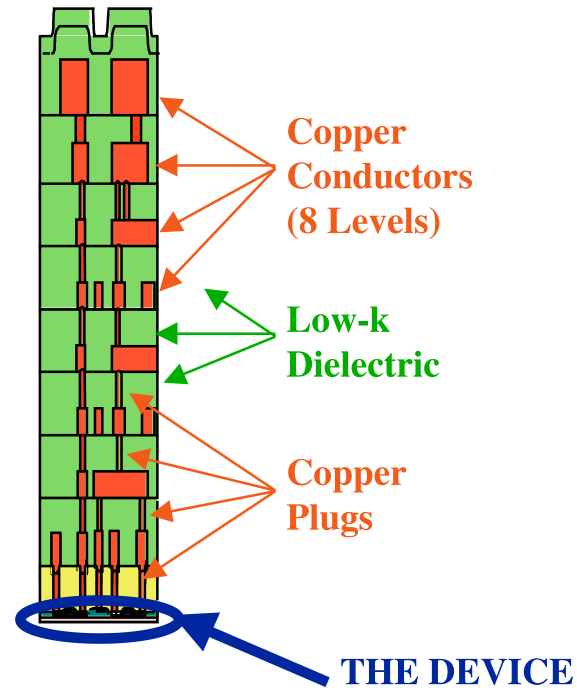

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Shockley's Seminal Contribution

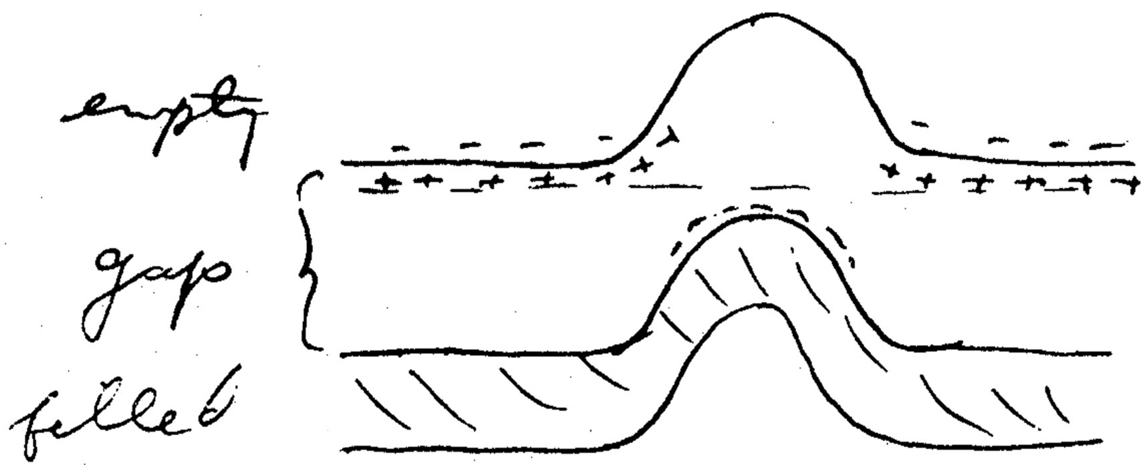
- **Shockley presented his seminal contribution during Feb 18 '48 meeting with Shive, Bardeen, Brattain, et al.,**
  - Injection over barrier
  - Theory of p-n junctions
  - P-n junction transistor
- **Shockley's p-n junction and p-n junction transistor, originally notebook account not shared with Bardeen or Brattain, facilitated mathematical description of Bardeen and Brattain's previously disclosed semiconductor amplification (transistor action) by using one-dimensional, linear analysis**
  - ***Dec 31 '47***: Shockley developed early version of p-n-p junction approach (stripe device, no indication of minority-carrier injection)
    - Witnesed by Morgan Jan 6 '48 and Bardeen Jan 8 '48
  - ***Jan 23 '48***: Conception of Shockley's ***"347" patent*** identified injection concept (n-p-n structure)
    - Jan 27 '48: Witnessed by Haynes
    - Jul '48: Experimentally identified by Haynes and Shockley

Shockley's Path:Bipolar Junction Transistor

- ***Mar 12'47*: Preliminary theory of p-n junction resistance**
- ***Apr 4 '47*: Lightning arrestor, alternating p- and n-type layers**
  - Utilized "reverse-biased p-n junctions to collect minority carriers passing through intermediate layers"
- ***Apr 24 '47*: Diffusion theory of minority current to reverse-biased p-n junction**
  - Significant step clarifying concept of minority-carrier diffusion in steady-state, non-equilibrium conditions where majority carriers concurrently existed
  - Reverse-biased p-n junction boundary condition precluded discovery of minority-carrier injection and exponential increase with forward bias
- ***May 19 '47*: Theory of reverse currents in p-n junctions including Zener effect**
- ***Sept 16 '47*: n-p-n structure for high-frequency thermistor with electron flow over potential maximum of p-layer**

Shockley: September 16, 1947

- **"Action of thermistor may be limited at high frequency end due to time of relaxation of electrons or holes with their means of origin (dopants, acceptors, intrinsic traps, etc.) Limitation can be overcome by making thermistor action depend not upon varying number but instead upon** ***varying ability of electrons to cross barrier depending upon their temperature. Thus, if very thin layer of p material is sandwiched between layers of N to produce potential distribution shown below, these electrons can climb over barrier only if their energies are high enough. This will give an exponential resistance variation with temperature."***



After Shockley (courtesy Riordan)

Shockley's Path:Bipolar Junction Transistor

- ***Sept 16 '47*: n-p-n structure for high frequency thermistor with electron flow over potential maximum of p-layer**
  - Considered minority carrier flow through intermediate layer in n-p-n structure
  - Carriers emitted into p-region increases exponentially with temperature (rather than with forward voltage across p-n junction)
  - Advanced theoretical framework for development of semiconductor triode amplifier operating within confines of bulk semiconductor (i.e., bipolar junction transistor)

Shockley's Magic Month: Dec 24 '47 - Jan 23 '48

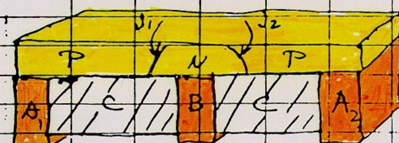
Received by mail from Chicago Jan 5, 1948
Read and understood by me Jan 6, 1948
S. O. Morgan

II. 2

There is no II. 1

Voltage and Current Amplification using N-P junction

There are a number of possible ways of utilizing an N-P junction in amplification. The figure shows ~~a bo~~ two blocks of ceramic between which there is



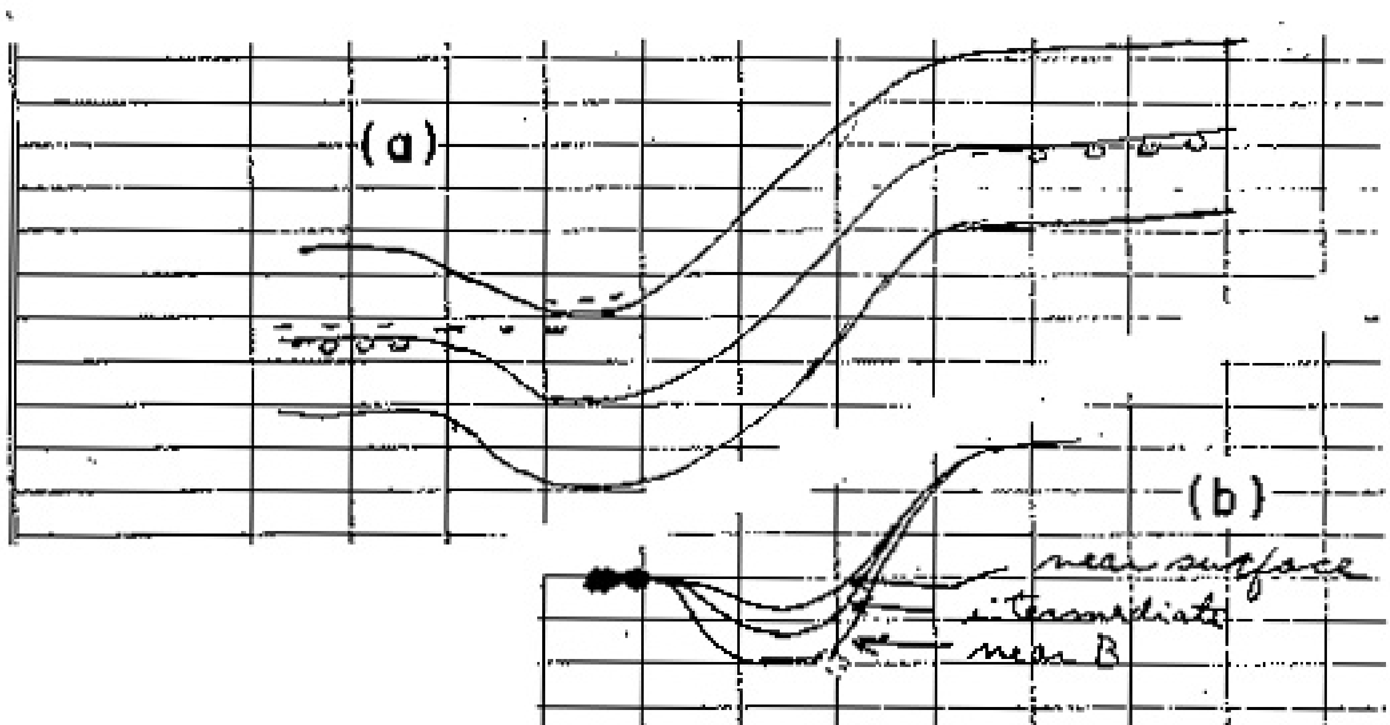
a layer of antimony bearing alloy "B". At the ends of the block are electrodes A which make low resistance contacts with P type Germanium. P type germanium in a thin film is ~~layed~~ laid down on the block and is heat treated so that the antimony produces a thin section of N-type around B.

Read and Understood Jan 9, 1948

After Shockley (courtesy Riordan)

Shockley's Magic Month:Dec 24 '47 - Jan 23 '48

- ***Dec 31 '47*: Two p-type regions separated by strip of n-type**
  - Energy band diagram almost indistinguishable from "true" junction transistor
  - Missed possibility of minority-carrier injection into base layer (holes as minority carriers in the presence of majority-carrier electrons)

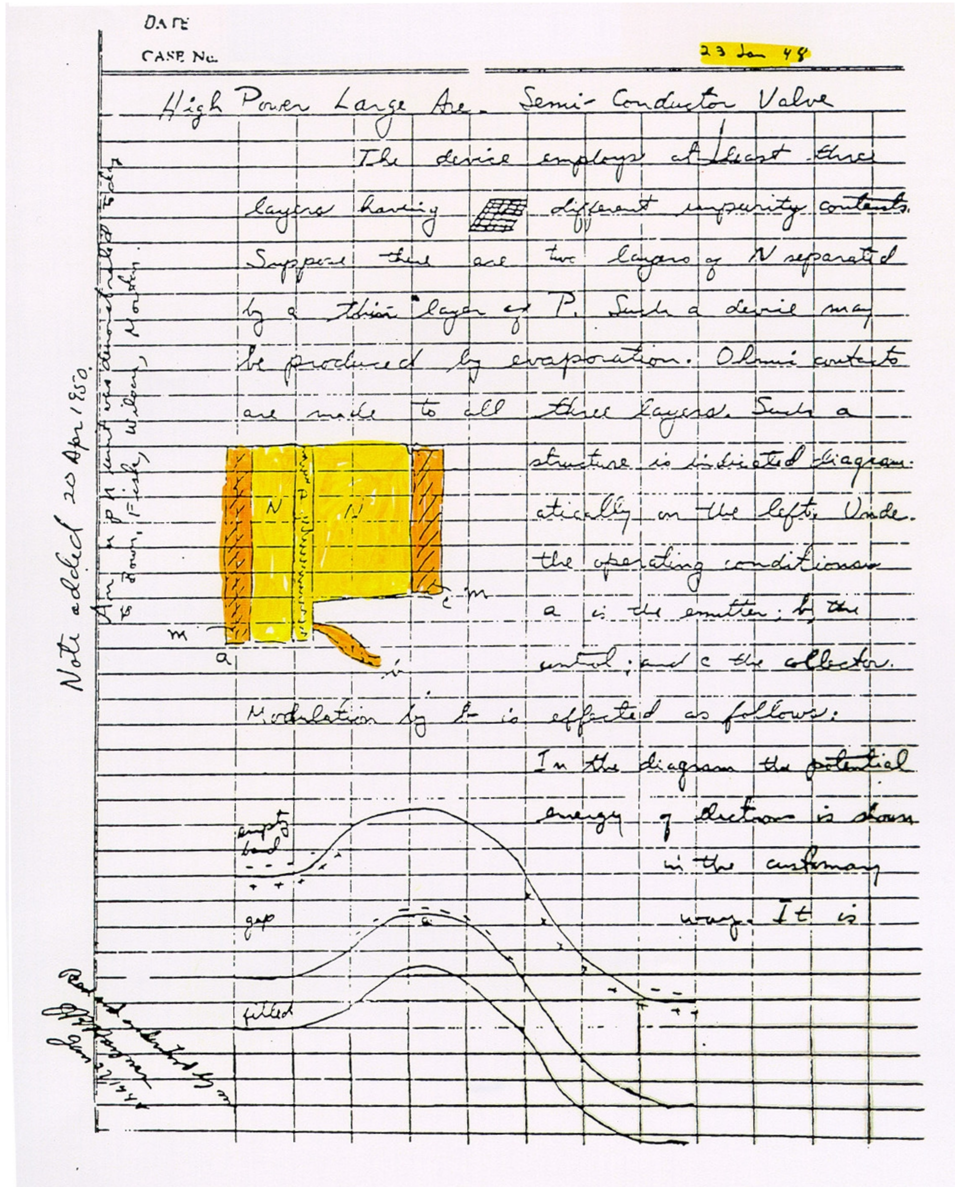


After Shockley (courtesy Riordan)

Shockley's Magic Month: Dec 24 '47 - Jan 23 '48

- **Jan 23 '48: Conception of Shockley's *"347" patent* devised while planning tests to determine if inversion layer critical to operation of point-contact transistor**
  - "Place n-type contact on top of assumed p-type inversion layer
  - Anticipated n-type contact would adjust to electrons in underlying n-type material rather than potential of holes in inversion layer
  - Electrical contacts applied to ***all*** three layers (including now the base) allowed better control of voltage levels in layers and differences between them
    - ***Intermediate layer in previous lightning arrestor and thermistor allowed to float at voltages imposed on them by neighboring layers***
    - "Strip"structure had independent voltage source but no interposed layer of sufficiently doped conductivity type lying between regions of opposite type
  - Structure with "three layers of semiconductor with alternating conductivity type examined in terms of three-terminal amplifying device"
  - "Possibility of current flow between two outer layers by minority carriers diffusing through middle layer
    - Recognized that one of the p-n junctions could be reversed biased and minority carriers could control reverse current"
  - ***"P-n junction semiconductor amplifier***, later called junction transistor

Shockley’s Magic Month:Dec 24 ‘47 - Jan 23 ‘48


DATE
CASE No. 23 Jan 48

High Power Large Area Semi-Conductor Valve

The device employs at least three layers having different impurity contents. Suppose there are two layers of N separated by a thin layer of P. Such a device may be produced by evaporation. Ohmic contacts are made to all three layers. Such a structure is indicated diagrammatically on the left. Under the operating conditions a is the emitter; b the control; and c the collector.

Modulation by b is effected as follows:

In the diagram the potential energy of electrons is shown in the customary way. It is

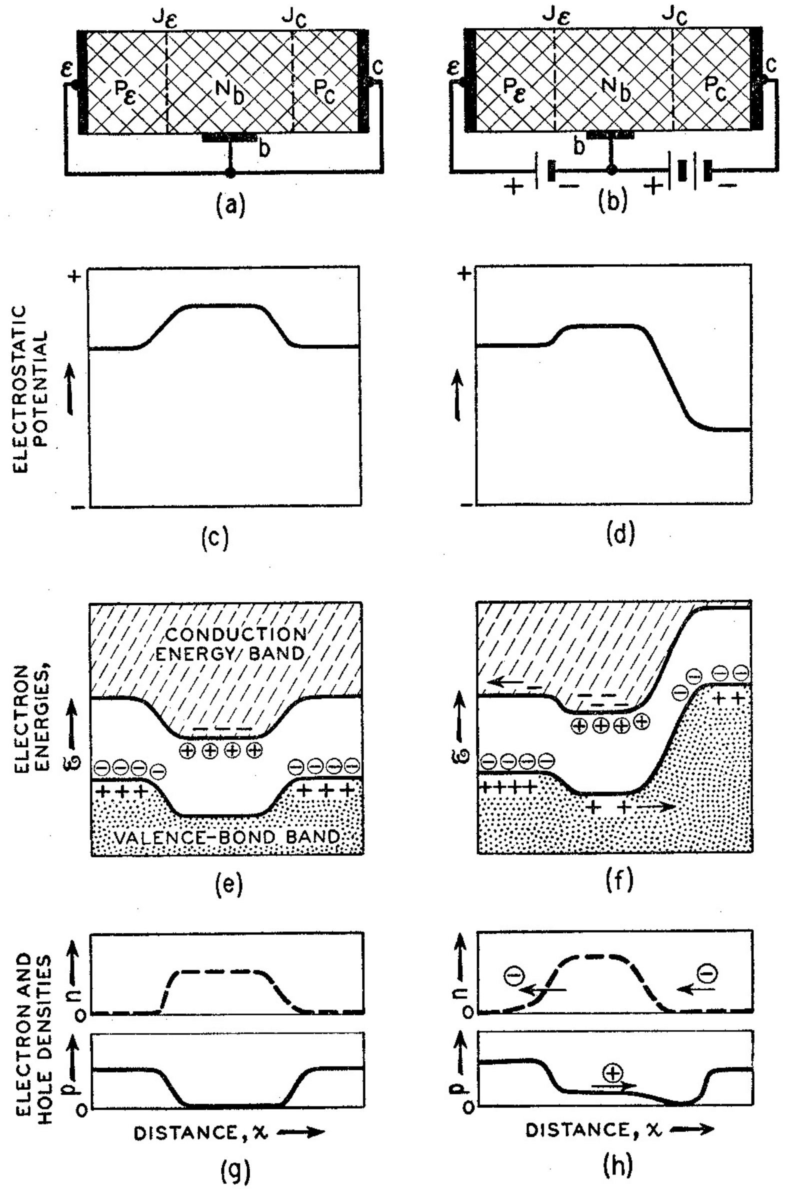
Note added 20 Apr 1950.

After Shockley (courtesy Riordan)

Shockley's Magic Month: Dec 24 '47 - Jan 23 '48

- ***Jan 23 '48*: Shockley identified injection concept (n-p-n)**
  - "It is to be observed that there is a potential barrier over which electrons must climb in order to go from a [emitter] to b [base]. This barrier is produced by the acceptor impurities in the P layer. The P layer is so thin or so slightly excess in P impurities that it does not produce a very high potential barrier. If now a ***positive potential is applied at b [base]***, whose contact is such that ***holes flow easily into the P layer***, these holes will flow into and throughout the P layer ***thus lowering its potential for electrons***. This will ***increase the flow of electrons over the barrier exponentially***. Since the ***region to the right of the P layer [collector] is being operated in the reverse direction, practically all of the electrons crossing the barrier reach it so that the output is essentially higher impedance. This will lead to voltage and power gain."***

Bipolar p-n-p Junction Transistor



After Shockley

Bipolar Junction Transistor (Critical Concepts)

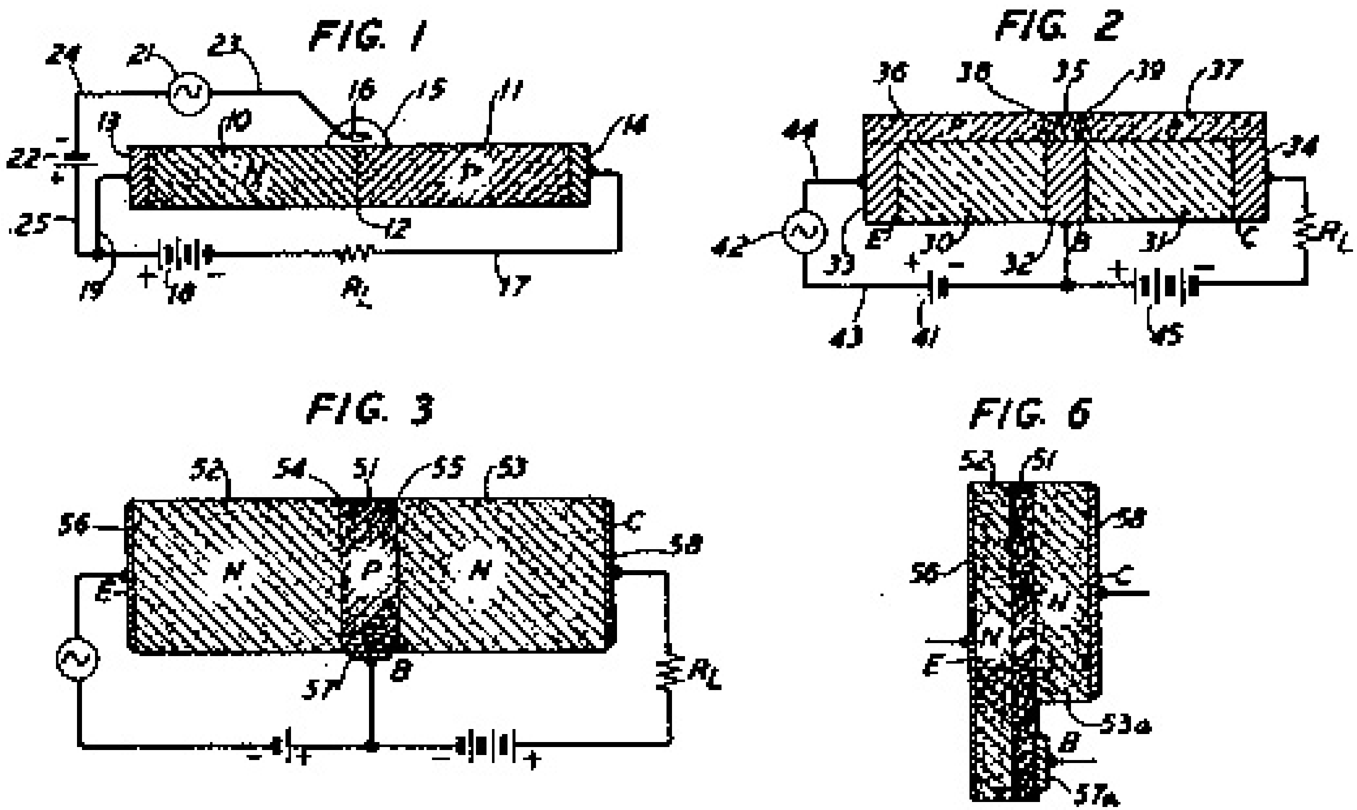
- **"This n-p-n device finally contained key concept 'exponentially increasing minority-carrier injection across emitter junction'" with forward emitter bias**
- **Application of reverse voltage bias at collector junction**
  - Potential barrier exponentially reduced during forward emitter bias increased flow of electrons into adjacent p-type base en route to reverse biased base-collector junction where electrons accelerated to collector

$$I = I_o\,([\exp\,(qV/kT)] - 1)$$

- **Favorable geometry and doping levels to obtain good emitter to collector efficiency**
- **Electrons (minority carriers) flowed in presence of dominant holes (majority carriers) in p-type base region**
  - Critical outstanding question: Minority carrier survival during transit through base material $\Rightarrow$ strongly dependent on properties of semiconductor
- **High output impedance at base-collector junction developed as result of reverse-bias, central concept for voltage gain**

Shockley’s Magic Month:Dec 24 ‘47 - Jan 23 ‘48

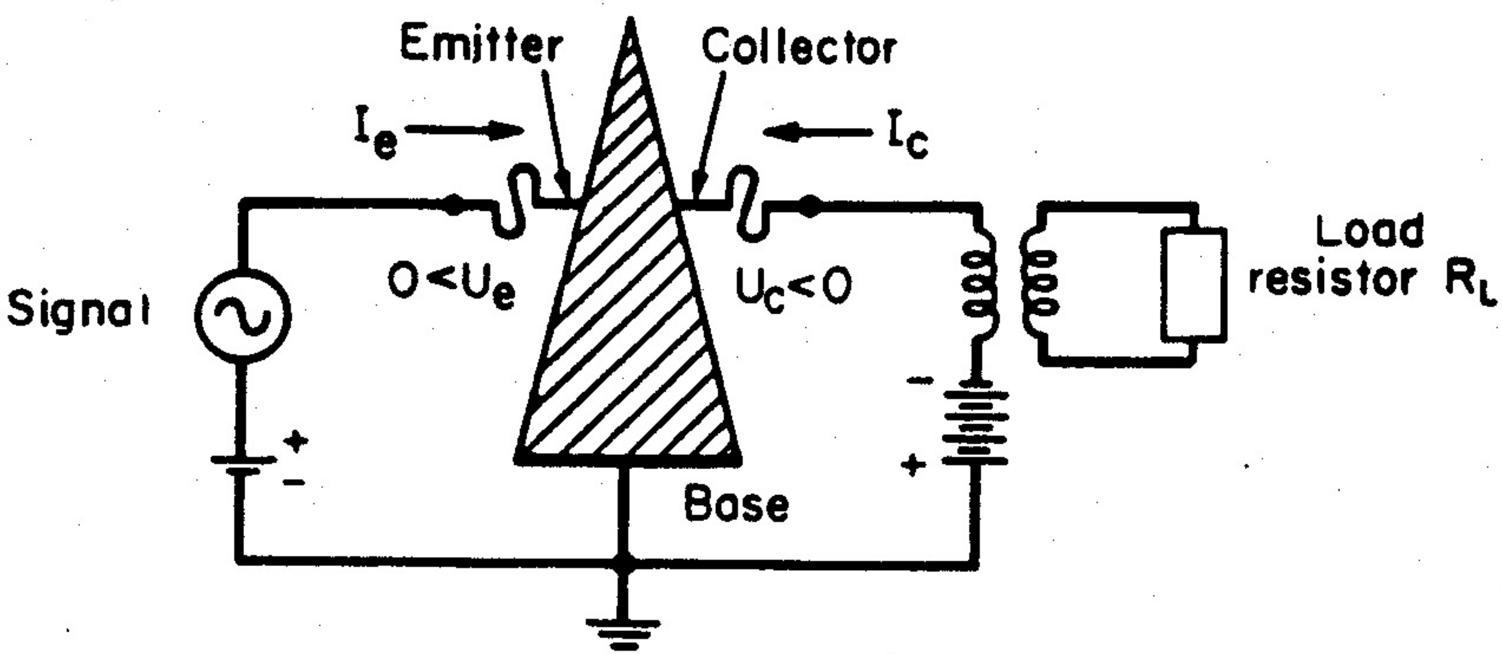
- *“347” patent* **sufficiently broad to include electrolyte across p-n junction amplifier as well as three-layer junction transistor, although “we did not know how to make them [the latter device]”**



After Shockley’s “347” patent

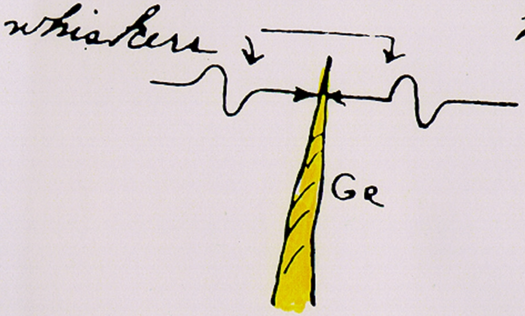
Shive's Double Surface Transistor (Feb 18 '48)

- **Shive explicitly illustrated influence of transistor geometrical configuration on transport path of minority carriers**
  - Emitter and collector placed on opposite surfaces (≈ 100 µm separation through bulk)
  - Shive's explicit experimental proof that minority carriers could flow "appreciable distances through the bulk of n-type germanium"



After Shive (Spenke)

Shive's Double Surface Transistor (Feb 18 '48)



Took a shiver of the above prepared slice and ground it down some more, both sides, to a thin tapered edge. Then etched for 5 mins in std etch. The edge was abt .001" thick. Made contacts, with phos bronze points, near the edge, with one point in input ckt as above and one point in output ckt. Gains from 12 to 44 were obtained, the latter being with the points back more than 1 mm from the edge. The Ge was abt .002" thick at this point.

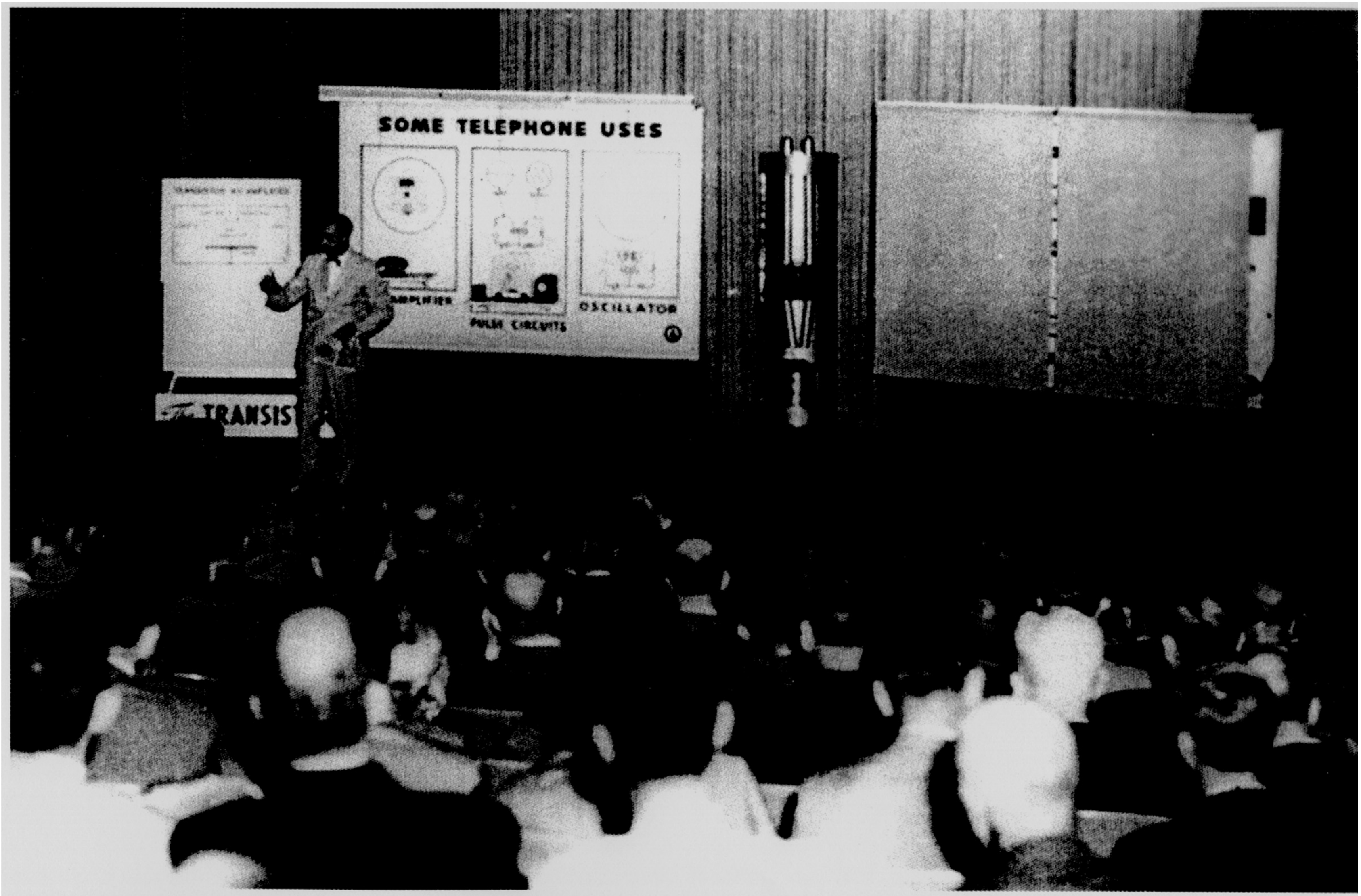
I envision using this effect as a triode principal. The geometry is less exacting than for ~~[illegible] "surface states"~~ effect, and the present discovery lends itself to easy cartridge mounting. In particular the solid state group's triode assembly

After Shive (courtesy Riordan)

Bipolar Junction Transistor (Injection)

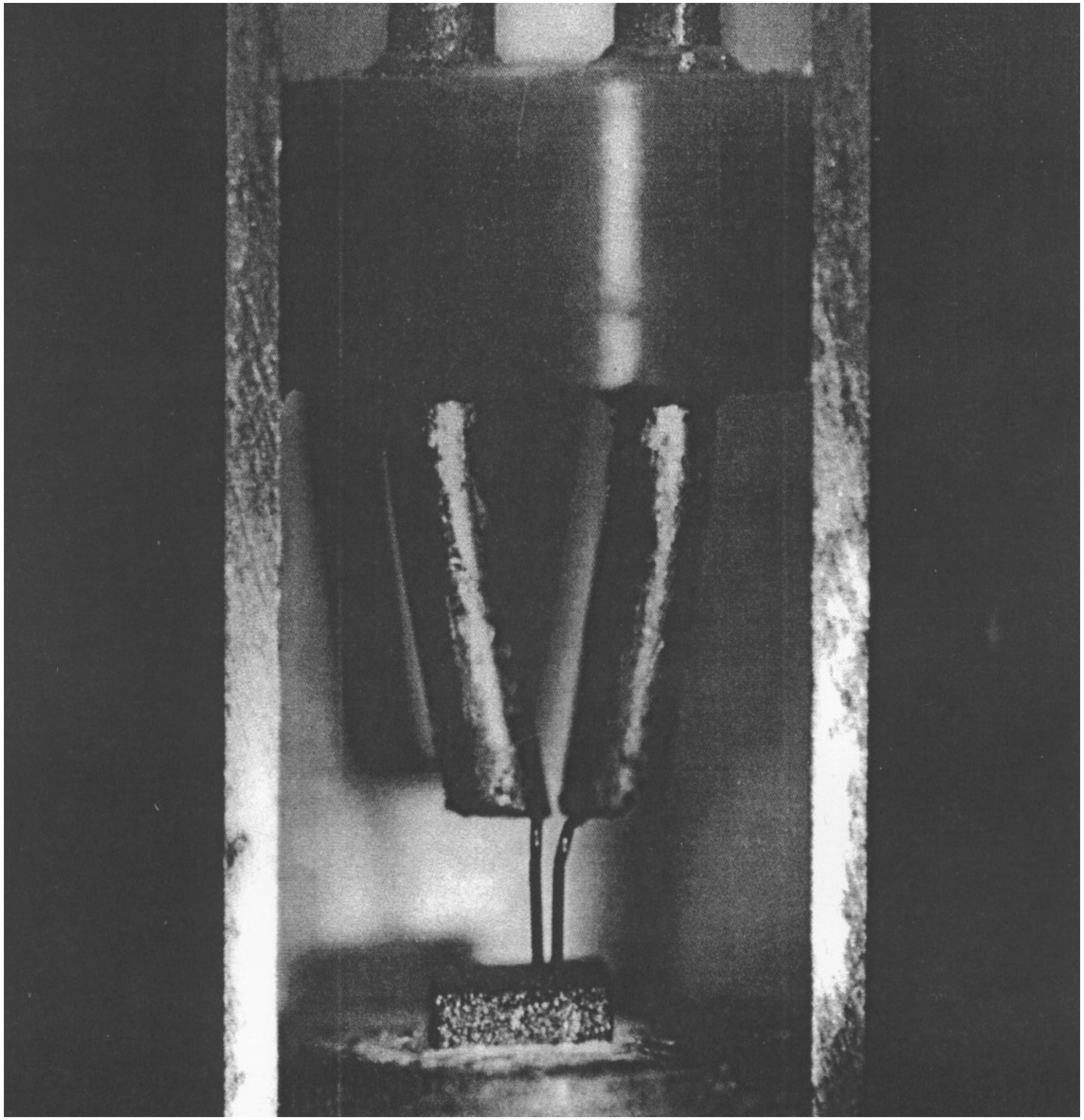
- **Several key concepts of junction transistor theory developed *after* junction transistor invented**
  - ***Jun 7 '48***: First version of Haynes-Shockley drift-velocity experiment showing positive point injects holes into n-type bulk Ge (drifting in electric field)
  - ***Dec 1 '48***: Ryder and Shockley show hole injection substantially reduces bulk resistance of n-type Ge

The Press Announcement - June 30, 1948



After Riordan

Point-Contact Semiconductor Amplifier (Type A)



After Riordan

The Press Announcement - July 1, 1948

The News of Radio

Two New Shows on CBS Will Replace 'Radio Theatre' During the Summer

Two new shows are announced by CBS to serve as summer replacements for the hour-long "Radio Theatre" on Monday evenings. The first, to be heard at 9:30 P. M., will be "Mr. Tutt," based on the stories of the late Arthur Train. Willard Wright will have the title role and Arnold Perl will do the adaptations. It will make its debut next week.

The second, to open on July 12, will be "Our Miss Brooks," with Eve Arden playing the role of a school teacher who encounters a variety of adventures. It will be written by Al Lewis and Lee Loeb, with Larry Berns serving as director. "Our Miss Brooks" will be offered at 9 P. M. Mondays.

A situation comedy with musical overtones, headlined by Mel Torme, has been selected as the replacement for the Dinah Shore-Harry James program at 8 P. M. Tuesdays over NBC, starting next week. The supporting company will include Janet Waldo and John Brown. Harmon Alexander and Ben Perry will do the script. Frank Danzig will be the producer and Ben Elliott, the musical director.

Station WFUV, Fordham University's frequency modulation outlet, will observe the completion of its first year of operation today. Throughout the day there will be special programs to mark the occasion and a number of personages on local commercial stations will participate, including John McCaffrey, Eileen O'Connell, Pat Barnes, Mary Small, Alma Dettinger and Arlene Francis.

At 8:05 P. M. there will be a critical discussion of present-day radio, the members of the panel including the Rev. Robert I. Gannon, president of Fordham; Morris Novik, John Garrison and F. W. Carlington.

"On Your Mark," a new audience-participation item, will be added to WOR's schedule next Monday. It will be heard at 2:30 P. M. each weekday afternoon thereafter and will include prizes for questions which are correctly answered. Paul Luther will produce and announce the program.

George Shackley's original composition, "Anthem for Brotherhood," will have its first television performance at 5 P. M. Sunday over WPIX. The rendition will be a part of the station's "Television Chapel" program.

Beginning tomorrow, "Waltz Time" will be heard for a full hour for three successive Friday evenings at 9 o'clock over NBC.

A memorial tribute to Col. David Marcus, who died in action while commanding the Israeli forces on the Jerusalem front, will be presented at 10:03 this evening over WMCA. Gov. Thomas E. Dewey and Mayor O'Dwyer will be among the speakers to be heard by means of transcriptions.

Station WNEW will transmit reports on traffic conditions on the major highways in the metropolitan area for those who plan to spend the holiday week-end out of town. On Friday, the reports will be heard on the hour at frequent intervals between 4 and 11 P. M. The same schedule also will be followed on Sunday and Monday afternoons and evenings.

"The Better Half," which is to go under commercial sponsorship on Sept. 16 over the Mutual network, will take to the air as a sustainer on Aug. 19.

A device called a transistor, which has several applications in radio where a vacuum tube ordinarily is employed, was demonstrated for the first time yesterday at Bell Telephone Laboratories, 463 West Street, where it was invented.

The device was demonstrated in a radio receiver, which contained none of the conventional tubes. It also was shown in a telephone system and in a television unit controlled by a receiver on a lower floor. In each case the transistor was employed as an amplifier, although it is claimed that it also can be used as an oscillator in that it will create and send radio waves.

In the shape of a small metal cylinder about a half-inch long, the transistor contains no vacuum, grid, plate or glass envelope to keep the air away. Its action is instantaneous, there being no warm-up delay since no heat is developed as in a vacuum tube.

The working parts of the device consist solely of two fine wires that run down to a pinhead of solid semi-conductive material soldered to a metal base. The substance on the metal base amplifies the current carried to it by one wire and the other wire carries away the amplified current.

After Riordan

Agenda

- Introduction
- Schottky-barrier diode
  - Rectification
- Point-contact semiconductor amplifier
  - Field effect / surface states
  - Minority carriers
  - Surface-states control
  - Magic month: Nov 17 '47 - Dec 16 '47
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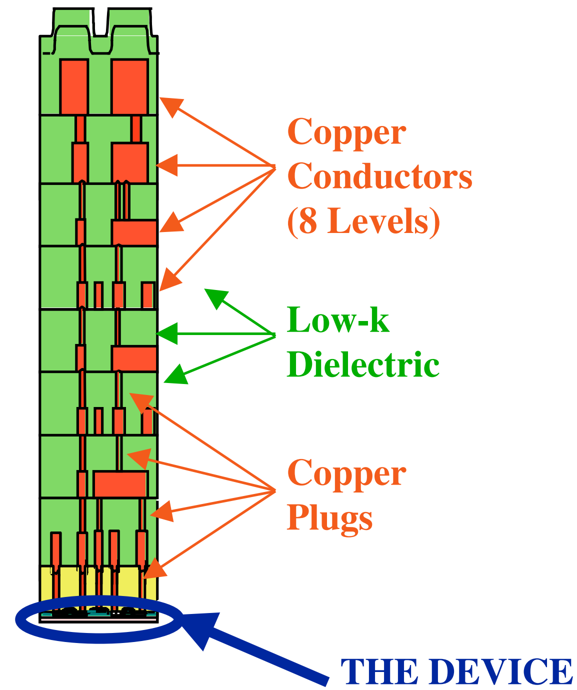
100 nm High End Microprocessor



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Bipolar Junction Transistor (Implementation) (The Bob Wallace Revelation)

- **Major goal to replace vacuum tube wherever possible, thereby requiring higher power at higher frequencies**
  - Transistor easiest to make small, favoring limited power-handling capability
  - Goal of increased frequency response required smaller, not larger devices
- **Chasing vacuum tube led to wrong emphasis; opportunity was created by focusing on transistor *in its own right***
  - Application for invention powerful stimulus for innovation
  - Original application may not be most important
  - Development should not be restricted to originally intended application
  - **"Gentlemen, you've got it all wrong! The advantage of the transistor is that it is inherently a small size and low power device. This means that you can pack a large number of them in a small space without excessive heat generation and achieve low propagation delays. And that's what we need for logic applications.The significance of the transistor is not that it can replace the tube but that it can do things the vacuum tube could never do!"**

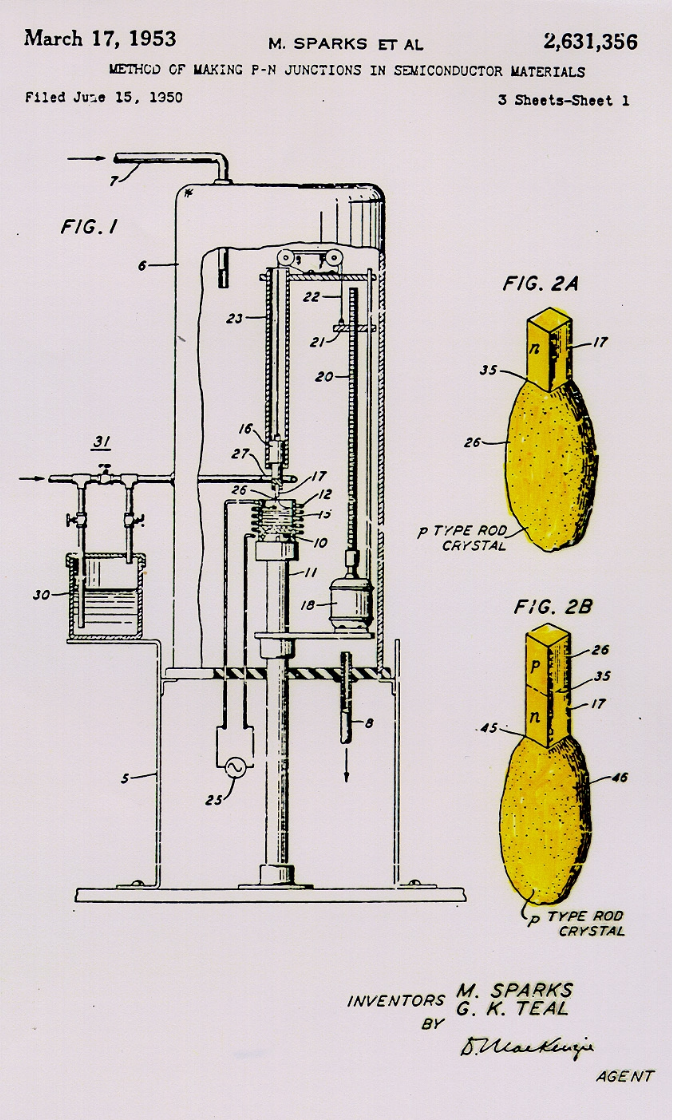
After Ross

Bipolar Junction Transistor (Implementation)

- ***Jun 26 '48*** **Shockley's p-n junction /p-n junction transistor theoretical analysis ("*347" patent* filed)**
- ***Apr 7 '49*** **Sparks/Mikulyak "existence proof" Ge p-n-p (non-colinear) transistor (power gain ≤ 16)**
- ***Jul '49*** **Shockley's extended p-n junction / p-n junction transistor theory published (Bell Syst. Tech. J.)**
- ***Apr '50*** **Teal/Buehler/Sparks single crystal research and fabrication of grown p-n junction and (double-doping) n-p-n large-area junction transistor (10-15 watts audio power ≤ 20 Kc)**
- ***Jan '51*** **Korean war stimulated fabrication of n-p-n microwatt junction transistor (proximity fuse)**
- ***Jul '51*** **Shockley, Sparks and Teal microwatt n-p-n junction transistor published (Phys. Rev.)**

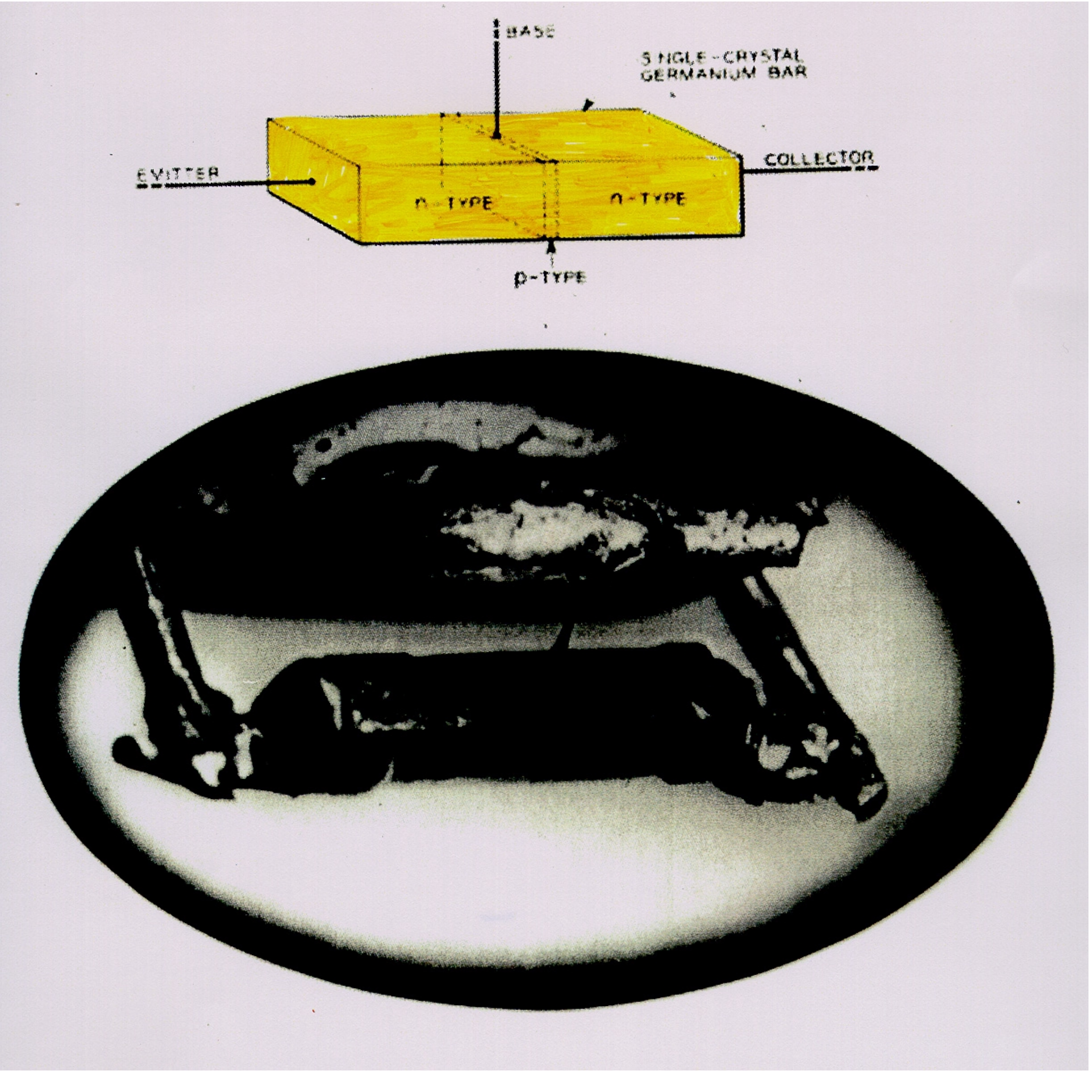
Bipolar Junction Transistor (Implementation)

Double-Doping Growth: N-P-N Large Area Junction Transistor



After Sparks et al. (courtesy Riordan)

Bipolar Junction Transistor (Implementation)
Microwatt Junction Transistor (July 4, 1951)



After Riordan

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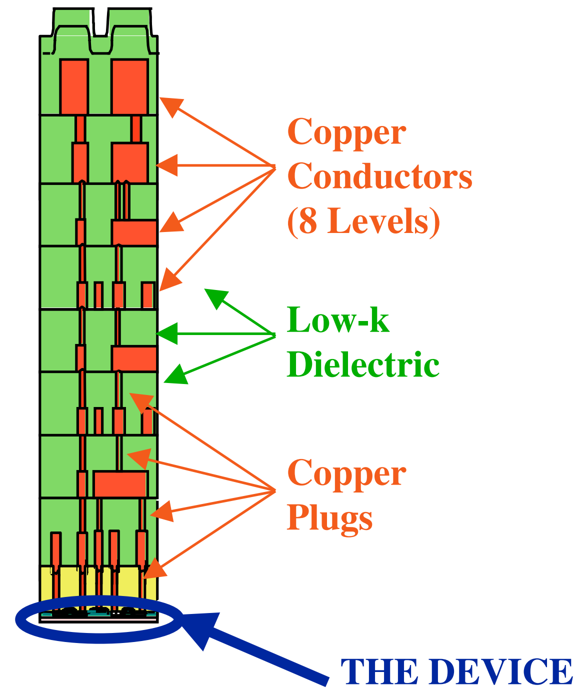

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Contemporaneous Events

- **Seitz et al. - University of Pennsylvania and Dupont (early '40s)**
  - **Purification methodologies for silicon and germanium**
- **Lark-Horovitz, Bray, Benzer, et al. - Purdue University ('42-'45)**
  - Bray observed spreading resistance anomaly in germanium as current spreads (from point contact into bulk of semiconductor)
    - Bray suggested decreased resistivity (factor 10-100) in n-type Ge due to electric field enhanced effects in high fields
      - $R_S = \rho/2d$ = slope of I-V curve
      - ρ = *local* resistivity near point contact and *d* = diameter of point contact
  - Bray also observed bulk resistivity reduced by high-voltage pulses
    - Subsequently interpreted as due to minority-carrier injection after BTL's publications
  - Hysteresis effect during rise and fall of voltage pulse
    - Current slow to rise and fall ($\tau \approx$ few μs)
  - Bray noted that Benzer also discovered p-type inversion layer on n-type Ge
- **"Bell people, knowing about our work, and how accidental was their own discovery, were fearful that we too might stumble upon the transistor and beat them to the priority of publication"**

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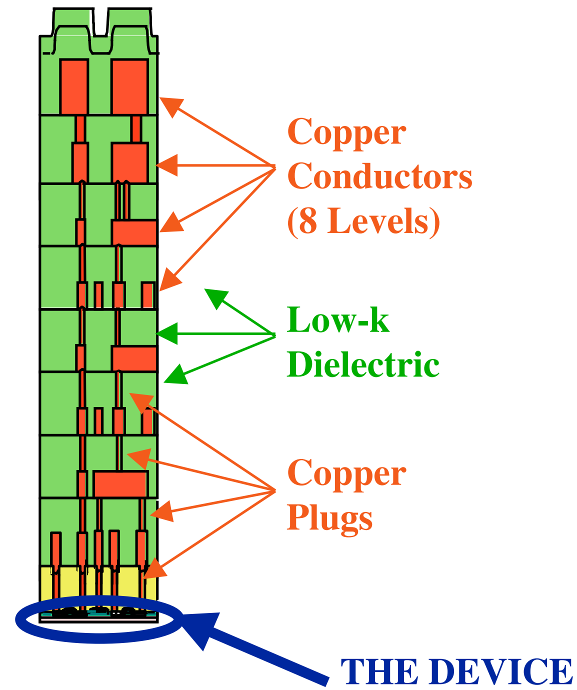

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Modern Silicon MOSFETs (Background)

- **Bardeen comprehended not efficient to modulate conductivity of slab of semiconductor via field effect**
  - Bardeen's research and "033" patent progenitor of MOSFET
  - Insulating gate modulating n-type inversion layer via field effect utilizing inversion layer to confine minority-carrier transport, in series with reverse-biased n-p junction
  - First recorded power gain in solid-state amplifier
- **Sah described device as sourceless MOS transistor**
  - Basis of, for example, subsequent MOS memory DRAM and CMOS microprocessor applications

Magic Month: Nov 17 '47 - Dec 16, '47

- ***Nov 23 '47*: Conception of Bardeen's *"033"patent* disclosure**
  - *Nov 22 '47*: "As noted by Brattain and Gibney ["034" patent] …. It occurred to the writer that the effect [semiconductor amplification] might be observed in the thin n-type layer on the surface of a block of p-type Si. It was suggested that this be tried because [CVD] thin films so far developed did not exhibit normal rectifying characteristics."
    - Insulating gate modulating n-type inversion layer via field effect
    - Inversion layer confines minority-carrier transport, in series with reverse-biased n-p junction
    - Dec 8 '47 formed inversion layer electrically rather than chemically
  - Described by Shockley (1973) as "an insulated gate field effect transistor (IGFET) with an inversion layer channel"
    - Re-canted by Shockley (1976) since patent referred to Gibney's ***"792" patent*** for preparing inversion layer on bulk semiconductor, rather than dynamically inducing inversion layer by gate voltage
  - Sah (1985) described device as sourceless MOS transistor

Modern Silicon MOSFETs

- *1955*: Ross's patent utilized ferroelectric as gate dielectric
- *1957*: Wallmark FET patent
- *1959*: Weimer thin-film FET utilized CdS as gate dielectric
- *1959*: Atalla et al. proposal of thermally grown SiO_2 as gate dielectric and stabilization of silicon surface
- *1960*: Ligenza and Spitzer proposal of high-pressure steam oxidation of silicon
- *1960*: Kahng and Atalla's description of NMOSFET in patents/literature
- *1963*: Hofstein and Heiman's (MOSFET) IGFET

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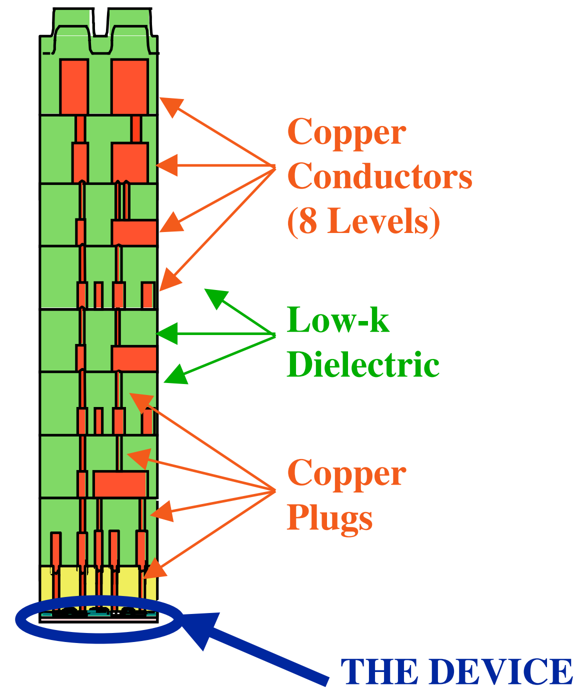

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Summary

- **Semiconductor amplification (transistor action) experimentally observed by Bardeen and Brattain in n-type polycrystalline germanium on Dec 15 ‘47**
- **Bardeen and Brattain noted large part of current flowed from emitter to collector as minority carriers in inversion layer**
  - Model calculation suggests non-trivial component of bulk transport possible
- **Shive clearly illustrated importance of geometrical configuration in determining extent of bulk transport**
- **Shockley’s seminal Jan 23 ‘48 contribution of injection over barrier, p-n junction theory and p-n junction transistor**
- **Bardeen comprehended Nov 23,’47 not efficient to modulate conductivity of slab of semiconductor via field effect and, thereby, patented first modern transistor device**
  - Insulating gate modulating an n-type inversion layer via field effect, utilizing inversion layer to confine minority-carrier transport, in series with reverse-biased n-p junction

Summary (con't)

- "….. Nearly all present-day field-effect transistors make use of controlling flow in an inversion layer of opposite conductivity type adjacent to surface (such as n-type inversion layer on p-type silicon.) *I [Bardeen] have basic patent on use of inversion layer to confine flow. Present-day bipolar transistors are of junction type and based on patented structure Shockley invented* while planning experiments to elucidate dynamics of point-contact transistor. Bell Laboratories patent department was unable to obtain patent on Shockley's field-effect invention because of Lilienfeld's patents and others." *(Bardeen)*
- "It seems likely that *many inventions unforeseen at present will be made based on the principles of carrier injection*, the field effect, the Suhl effect, *and the properties of rectifying junctions*. It is quite probable that other new physical principles will also be utilized to practical ends as the art develops." *(Shockley)*

Summary (con't)

- **"This book [Electrons and Holes in Semiconductors] had its origins in a series of lectures given at Bell Telephone Laboratories in connection with the growth of the transistor program. It thus owes its existence basically to the *invention of the transistor by J. Bardeen and W.H. Brattain."* *(Shockley)***

Summary (con't)

- **John Bardeen, co-inventor of the point-contact transistor and inventor of the MOS transistor, may rightly be called the**

father of modern electronics

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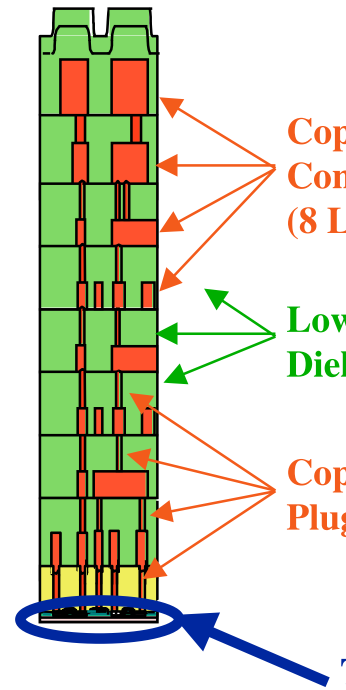

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Acknowledgements

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