半导体器件物理

马仁敏

北京大学物理学院

2017-2018学年第一学期

课程目标：

本课程将讲授半导体器件物理基础知识和器件应用最新进展，主要包括半导体电子器件物理和光子器件物理两大部分。包括二极管，晶体管，波导，激光器，调制器，太阳能电池，探测器等。

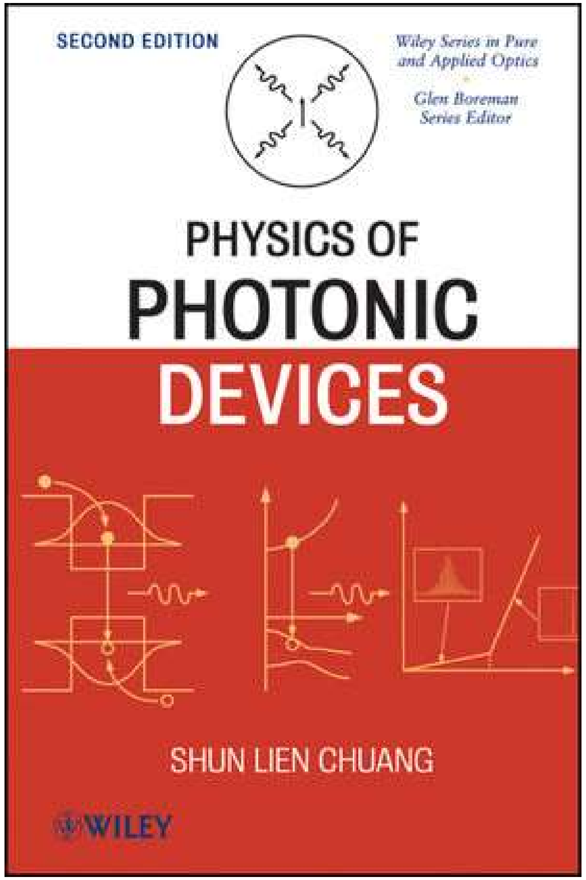
分数分布：

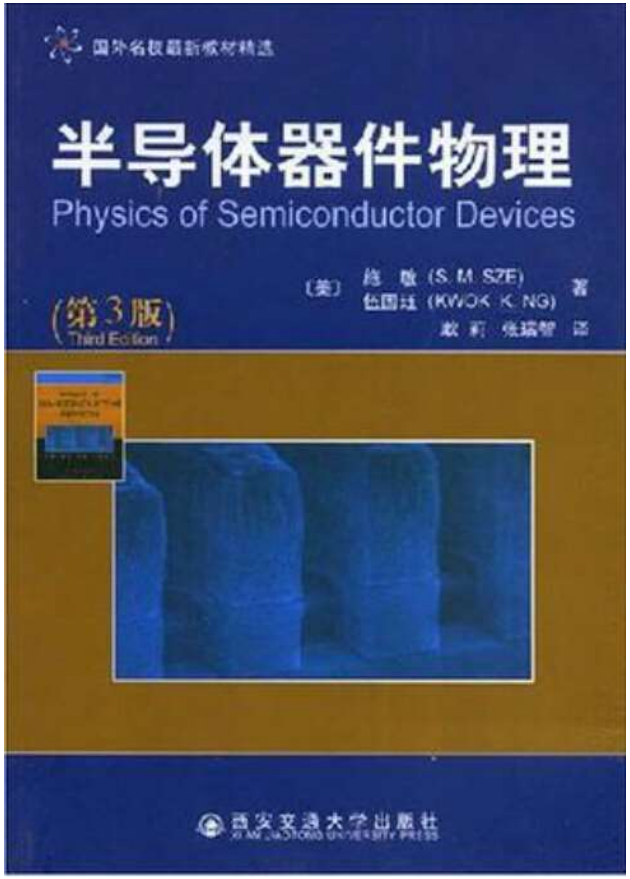
期末考试：50%

专题报告：30%

考勤：20%

主要参考教材：





教材：

《Physics of photonic device》作者：Shun Lien Chuang, Wiley 出版社，第二版，ISBN: 978-0-470-29319-5

《Physics of Semiconductor Devices》作者：Simon M. Sze, Kwok K. Ng, Wiley 出版社，第三版， ISBN-13: 978-0471143239

参考书：

– Yariv & Yeh, *Photonics: Optical Electronics in Modern Communications*, Oxford University Press, 2006
– Coldren & Corzine, *Diode Lasers and Photonic Integrated Circuits*, John Wiley & Sons, 1995
– Saleh & Teich, Fundamentals of Photonics, 2nd Ed. Wiley, 2007

REMEMBERING BELOVED FACULTY MEMBER SHUN LIEN CHUANG

Jonathan Damery, ECE ILLINOIS

3/28/2014

STORY HIGHLIGHTS

ECE Professor Emeritus Shun Lien Chuang passed away March 26, after an extended battle with cancer.

He will be remembered by students, faculty, and other collaborators for his affable and generous personality, in addition to his exceptional research career.

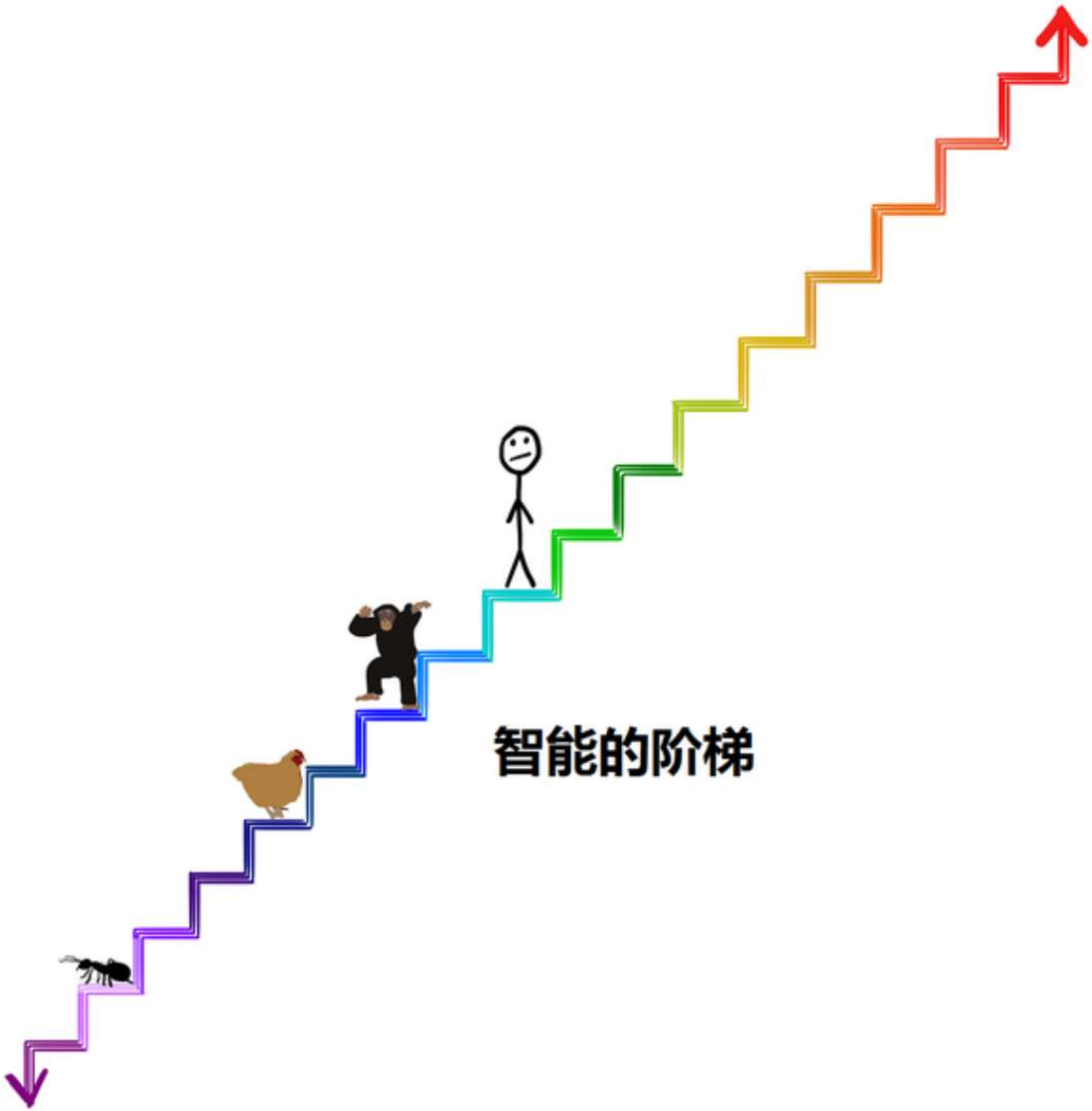
Chuang authored a leading textbook on the physical theories for lasers and allied devices. The second edition was published in 2009 with the title Physics of Photonic Devices (Wiley).

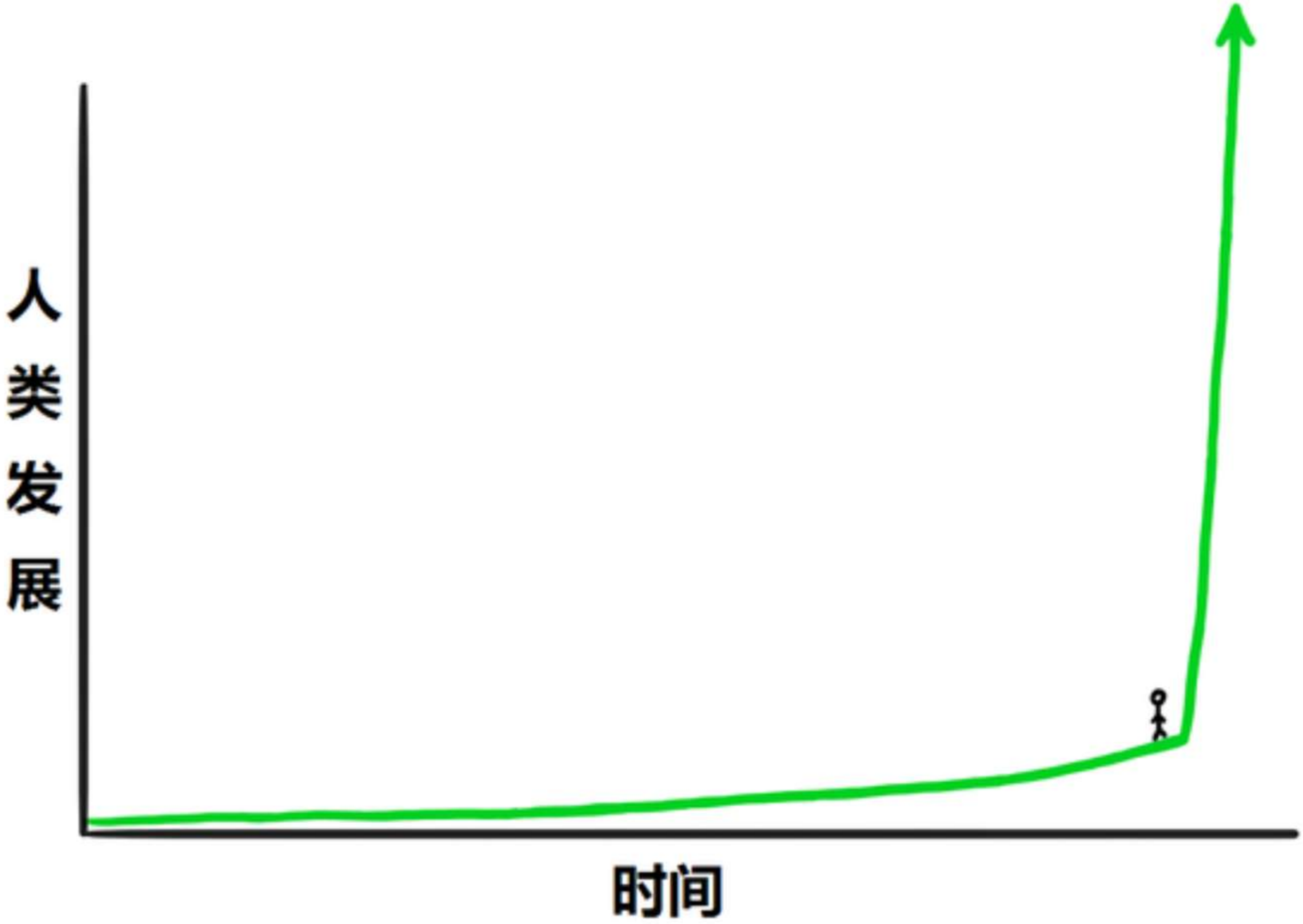
....

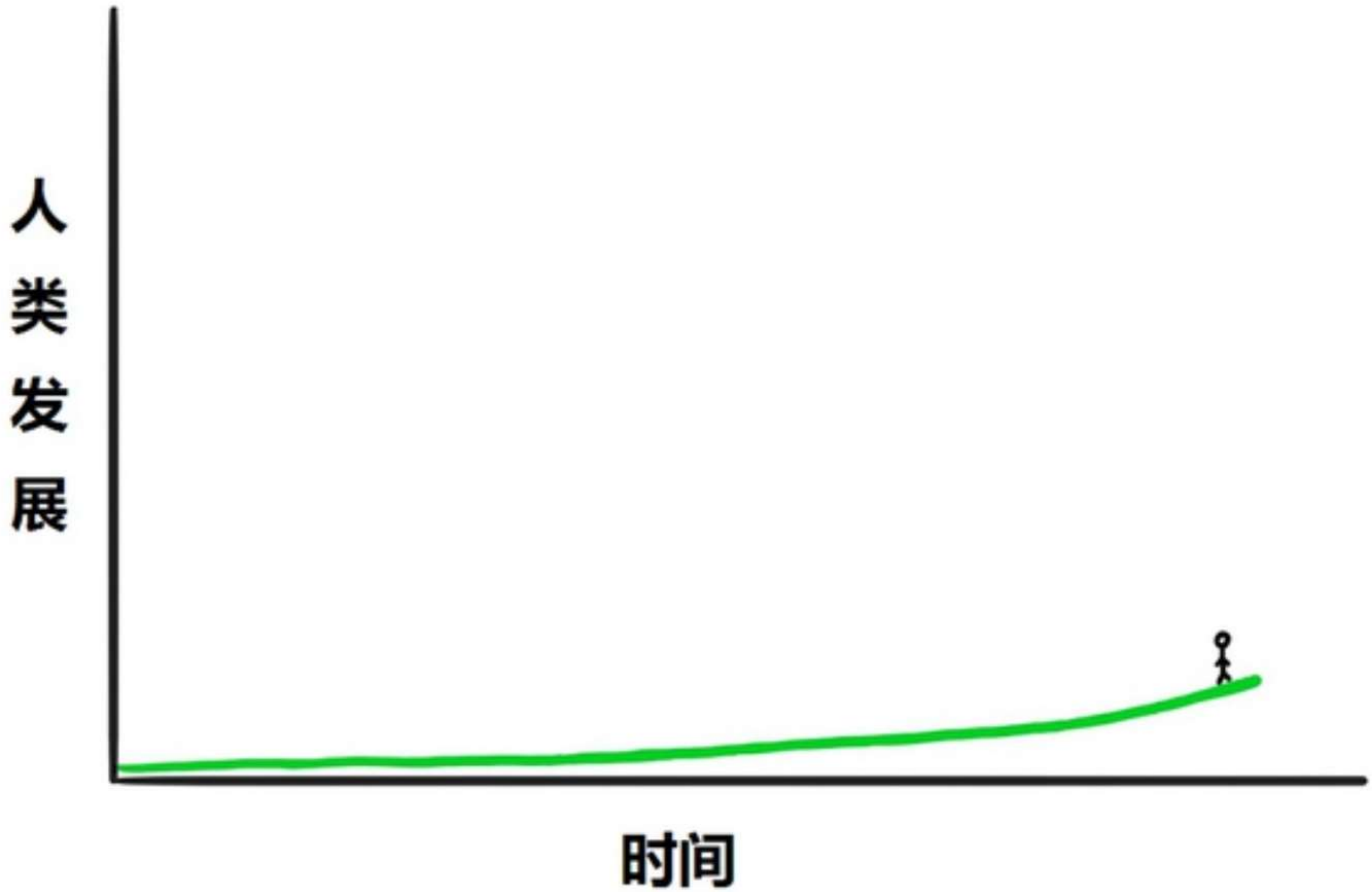
Late last year, Chuang recalled that after speaking at Intel, a number of engineers came to meet him afterward.

"They came to listen to me, do you know why?" Chuang said. "They came because they liked my book, even though it's a difficult book."

....


智能的阶梯


人类发展
时间


人类发展
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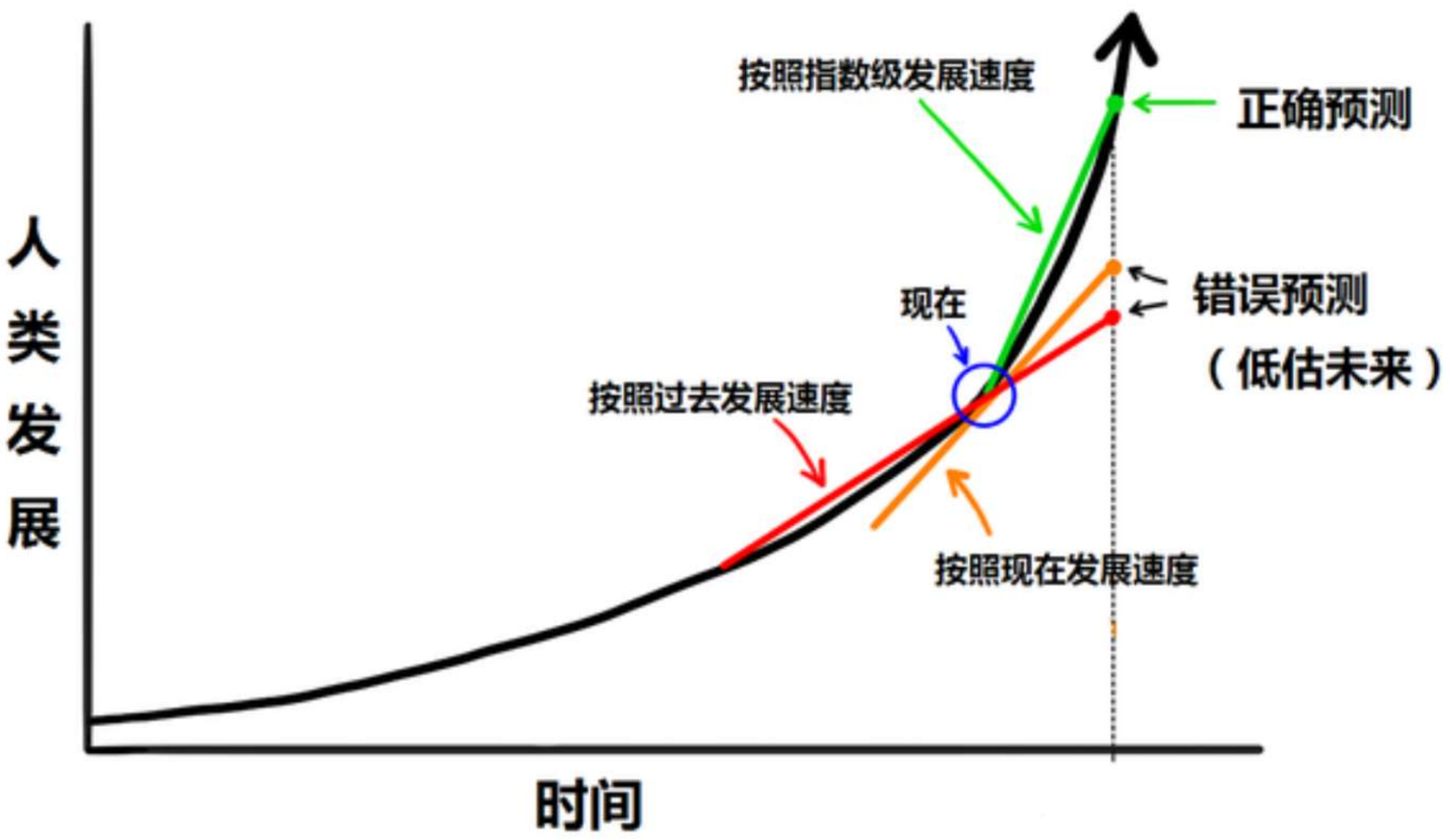

按照指数级发展速度
正确预测
人类发展
现在
错误预测
（低估未来）
按照过去发展速度
按照现在发展速度
时间


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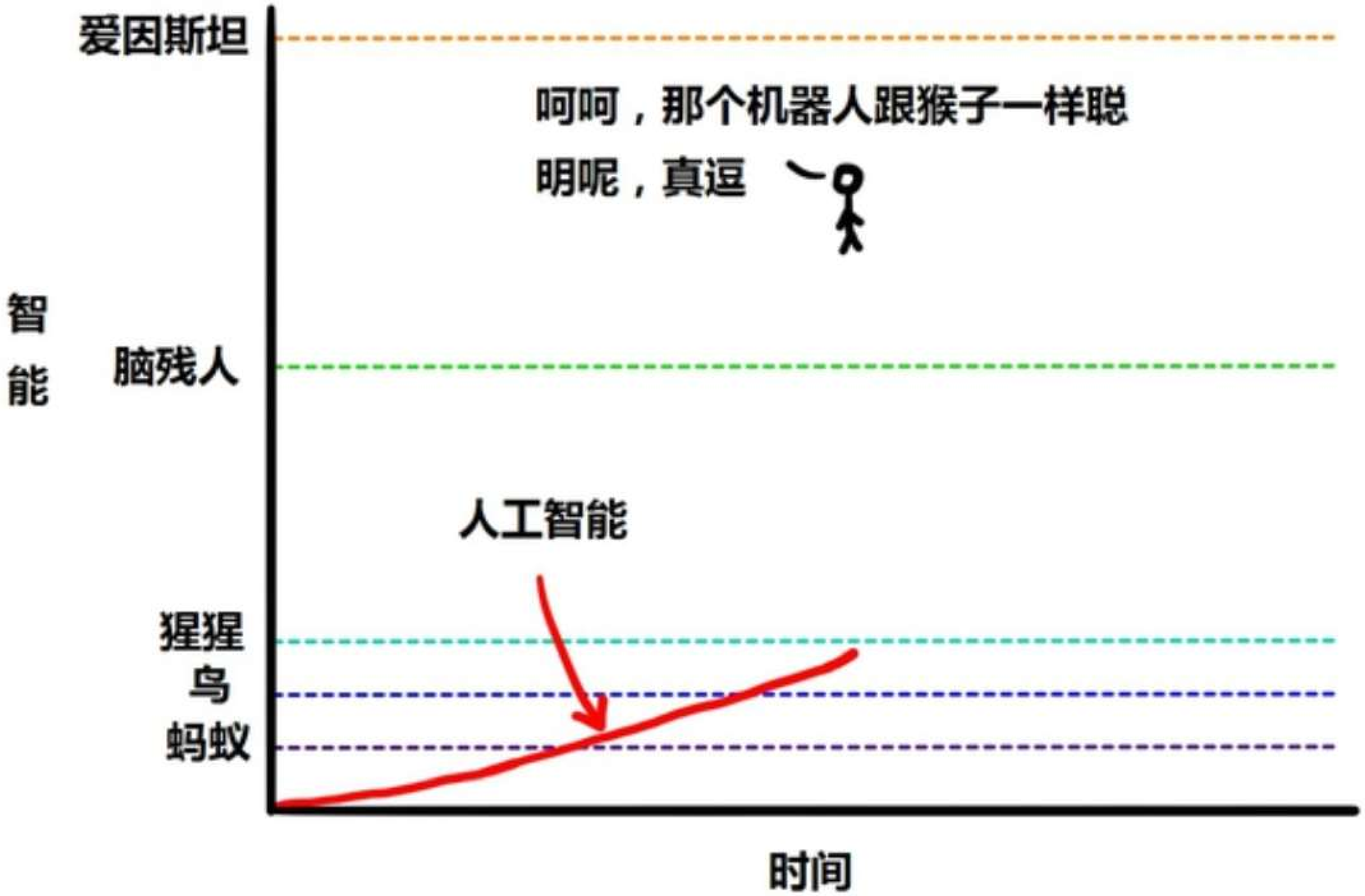
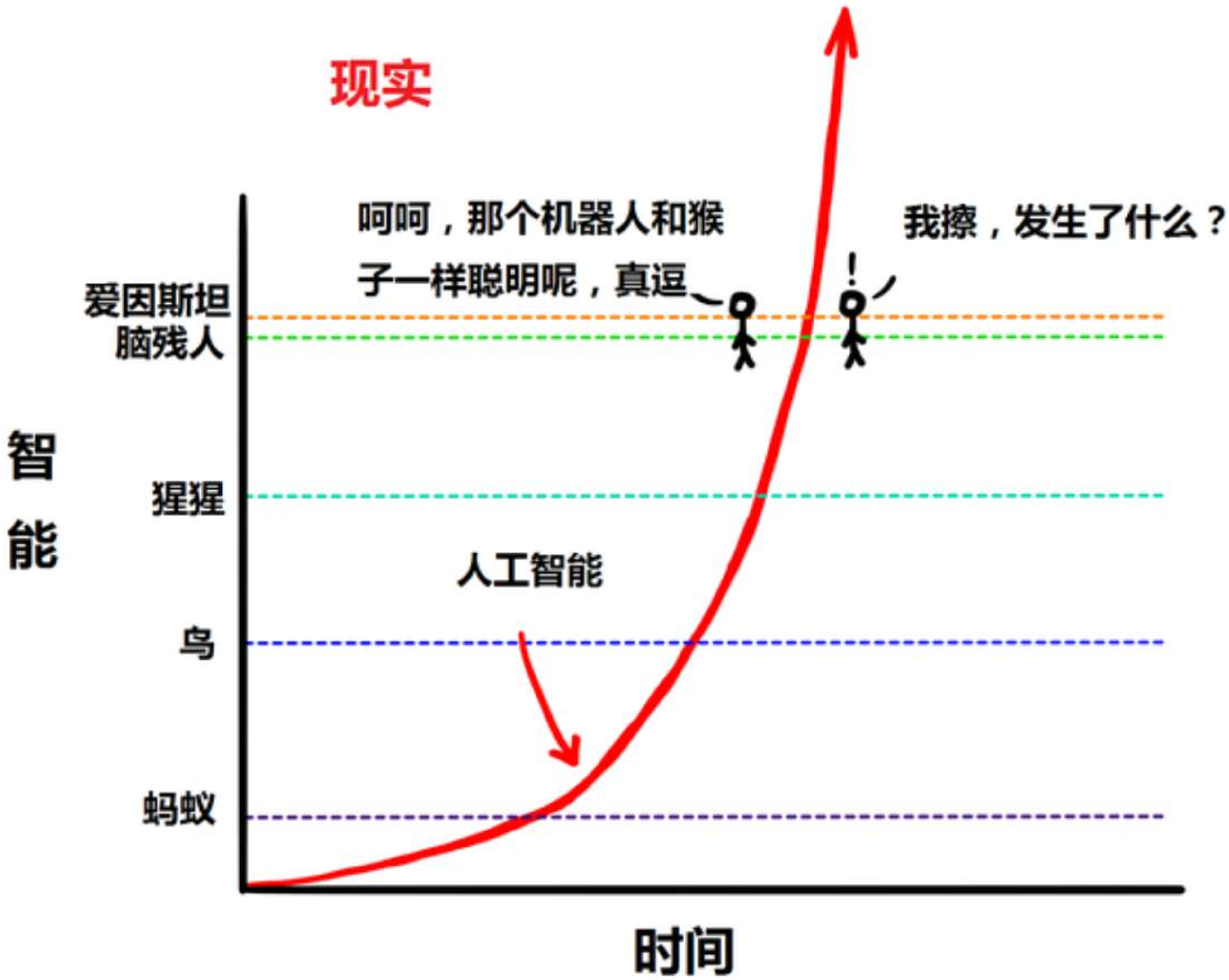
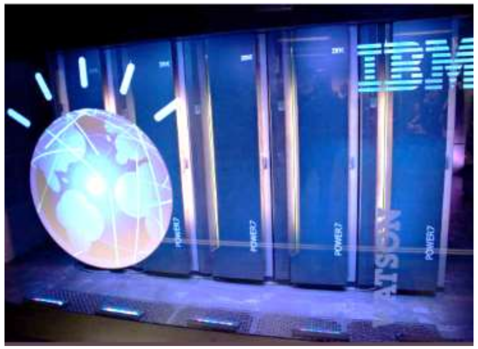
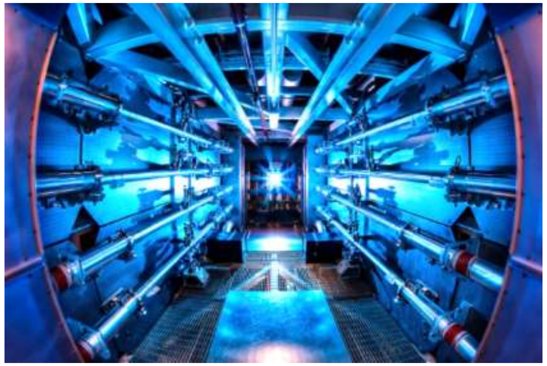


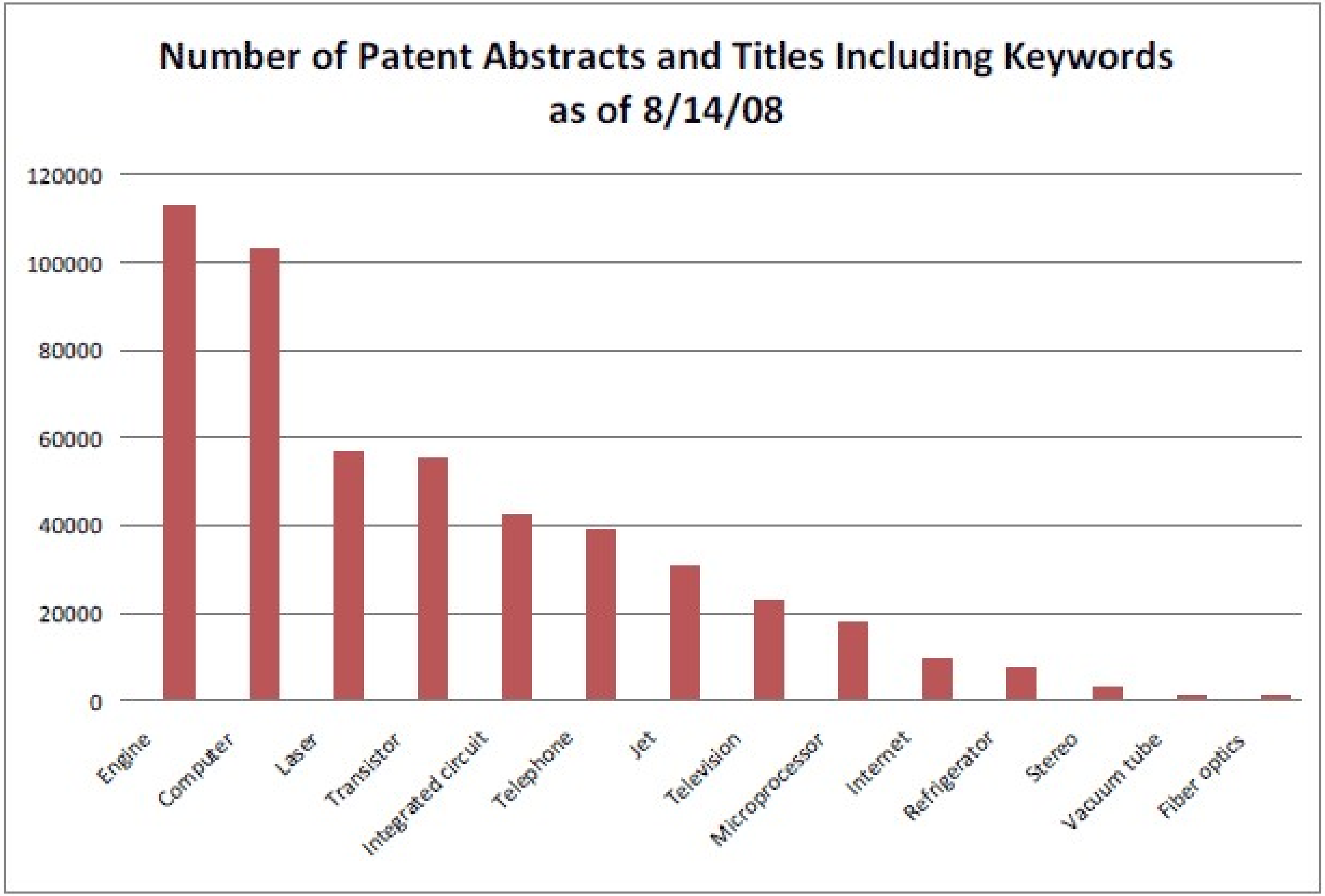
爱因斯坦
呵呵，那个机器人跟猴子一样聪明呢，真逗
智能
脑残人
人工智能
猩猩
鸟
蚂蚁
时间



一个故意不通过图灵测试的人工智能


IBM

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120000
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80000
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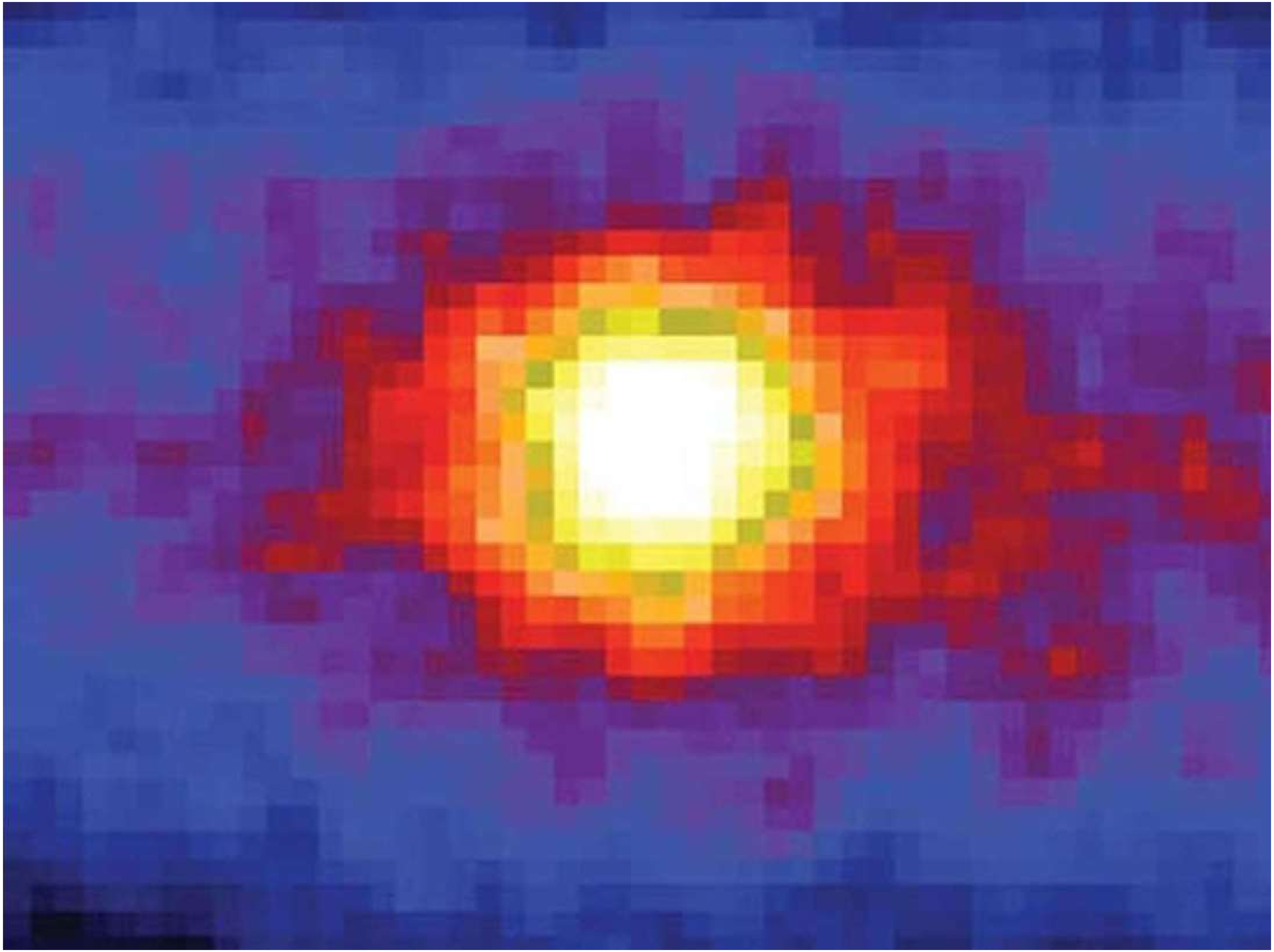


The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

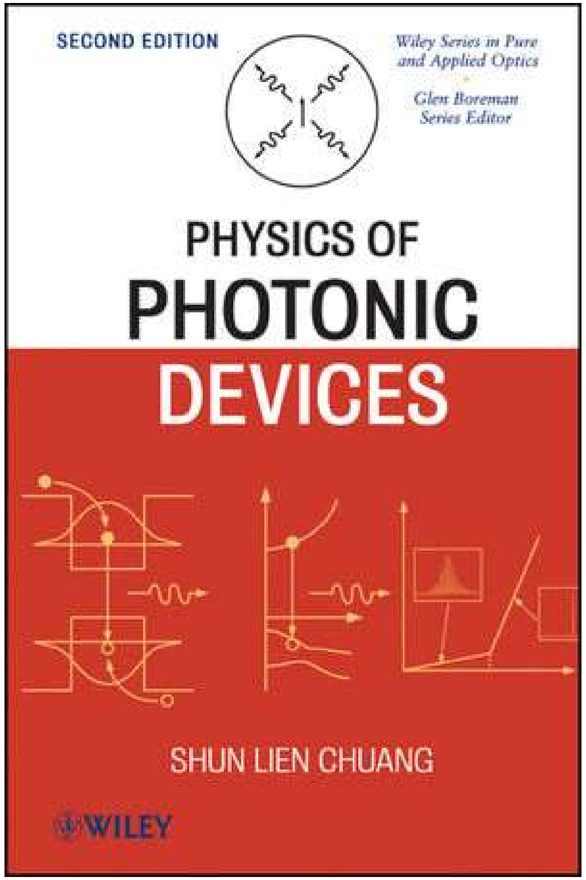
Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

主要参考教材：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SHUN LIEN CHUANG
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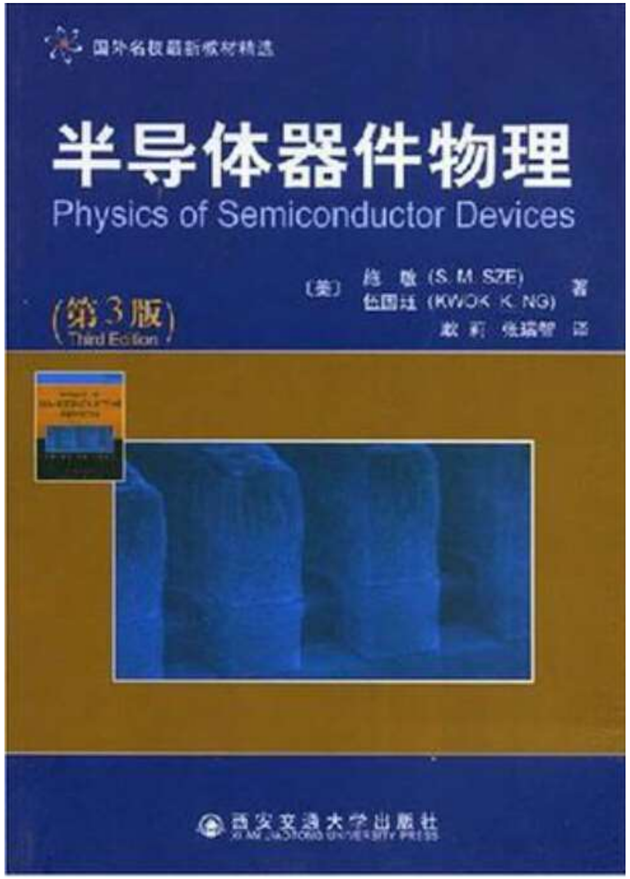
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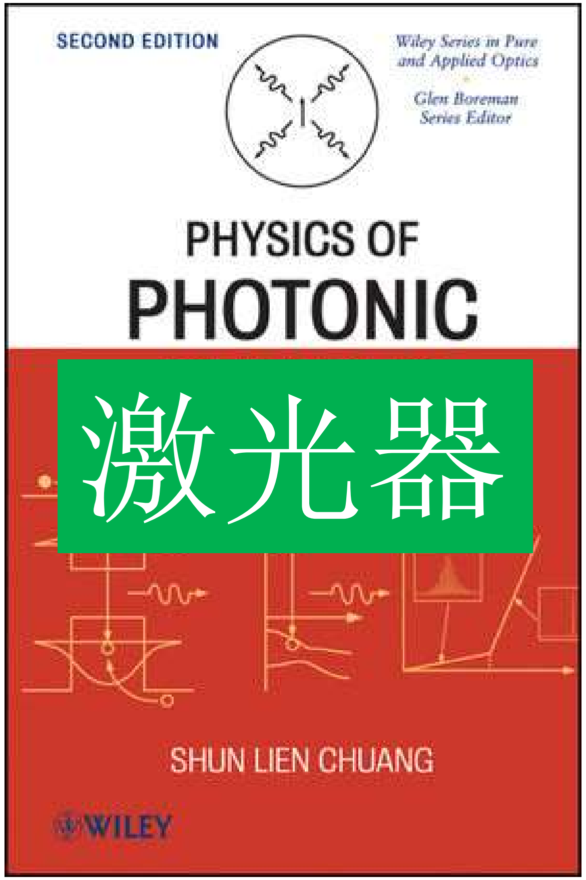
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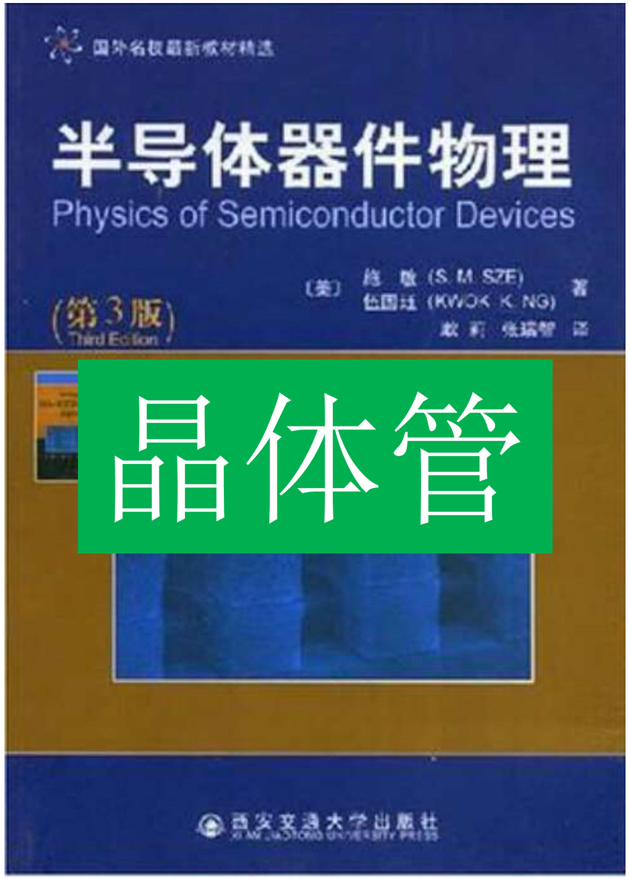
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晶体管

A brief history of transistor

The Nobel Prize in Physics 1956

William Bradford Shockley

Prize share: 1/3

John Bardeen

Prize share: 1/3

Walter Houser Brattain

Prize share: 1/3

The Nobel Prize in Physics 1956 was awarded jointly to William Bradford Shockley, John Bardeen and Walter Houser Brattain *"for their researches on semiconductors and their discovery of the transistor effect"*.

Continuation of Moore's Law

From Intel

Process Name	P856	P858	Px60	P1262	P1264	P1266	P1268	P1270
1st Production	1997	1999	2001	2003	2005	2007	2009	2011
Process Generation	0.25µm	0.18µm	0.13µm	90 nm	65 nm	45 nm	32 nm	22 nm
Wafer Size (mm)	200	200	200/300	300	300	300	300	300
Inter-connect	Al	Al	Cu	Cu	Cu	Cu	Cu	?
Channel	Si	Si	Si	Strained Si	Strained Si	Strained Si	Strained Si	Strained Si
Gate dielectric	SiO_2	SiO_2	SiO_2	SiO_2	SiO_2	High-k	High-k	High-k
Gate electrode	Poly-silicon	Poly-silicon	Poly-silicon	Poly-silicon	Poly-silicon	Metal	Metal	Metal

Introduction targeted at this time

Subject to change

Intel found a solution for High-k and metal gate

Importance

"The **Transistor** was probably the most important invention of the 20th Century."

Ira Flatow

- Transistors replaced vacuum tubes.
- Transistors are central to the Integrated Circuit, and therefore, all electronic devices of the information age, such as: pc's, cellular phones, ipods, pda's, intelligent cars and buildings…….. are made possible.

1874

- Ferdinand Braun discovered Rectification
  - crystals that can conduct current in only one direction under certain conditions.

- At the age of 24, as a graduate of the University of Berlin

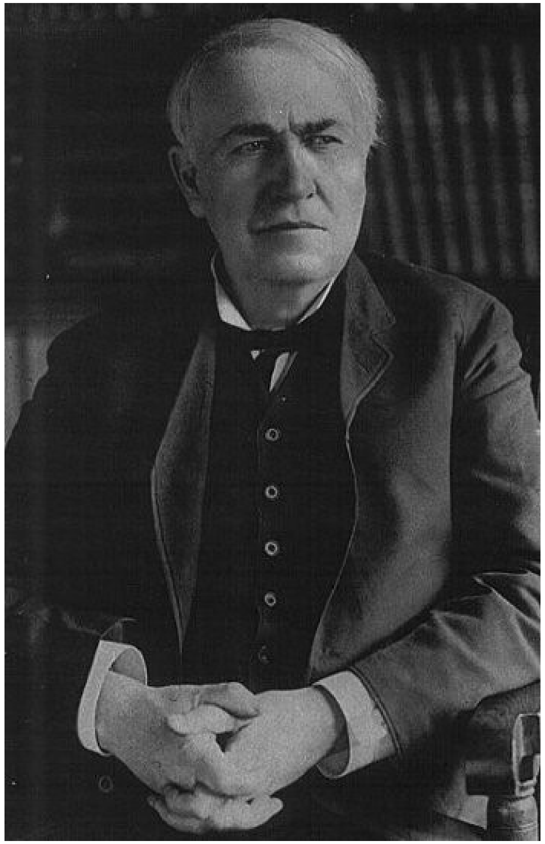
- Won the 1909 Nobel Prize in Physics for wireless telegraphy

http://en.wikipedia.org/wiki/Image:Ferdinand_Braun.jpg

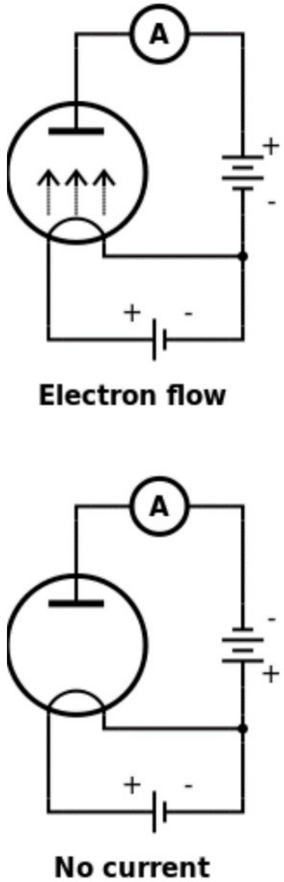
1883

- Edison effect (thermionic emission)

The flow of electrons from metals caused by thermal vibration energy (heat) that overcomes the electrostatic forces that hold the electrons to the surface.



Thomas Edison



1895

Guglielmo Marconi

Sent a radio signal over a distance of more than a mile.

- On 13 May 1897, Marconi sent the world's first ever wireless communication over open sea (a distance of 6 kilometres).
- On 12 December 1901, signal completely across the Atlantic

The Nobel Prize in Physics 1909

Guglielmo Marconi

Prize share: 1/2

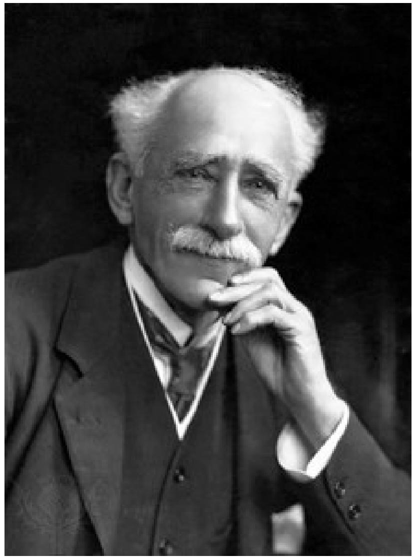
Karl Ferdinand Braun

Prize share: 1/2

The Nobel Prize in Physics 1909 was awarded jointly to Guglielmo Marconi and Karl Ferdinand Braun *"in recognition of their contributions to the development of wireless telegraphy"*

1895

- John Ambrose Fleming - developed the Vacuum Tube
  - a device that **modify** a signal by controlling the movement of electrons in an evacuated space.
  - The electrons flow only from filament to plate creating a diode (a device that can conduct current only in one direction)



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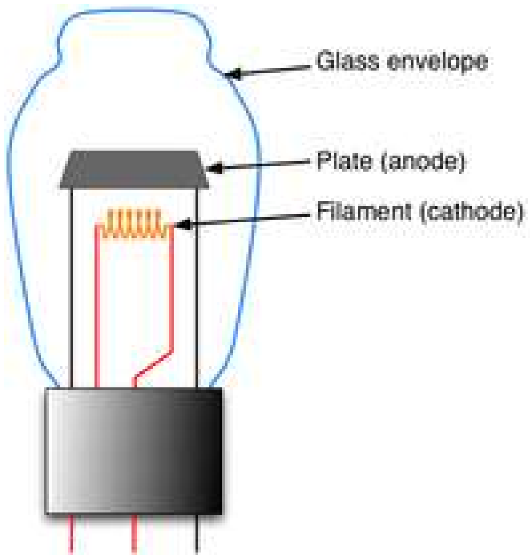


http://en.wikipedia.org/wiki/Image:
Diode_vacuum_tube.png

1898

- Joseph John Thomson discovered the electron.

http://en.wikipedia.org/wiki/Image:Jj-thomson2.jpg

The Nobel Prize in Physics 1906

Joseph John Thomson

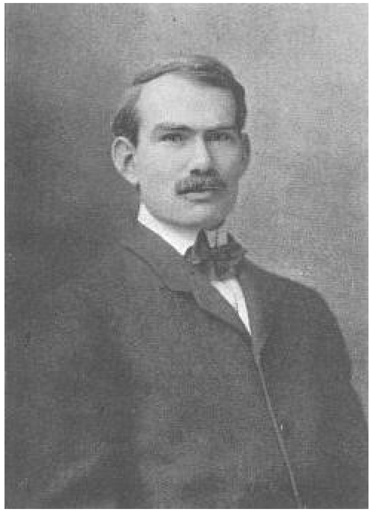
Prize share: 1/1

The Nobel Prize in Physics 1906 was awarded to J.J. Thomson *"in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases"*.

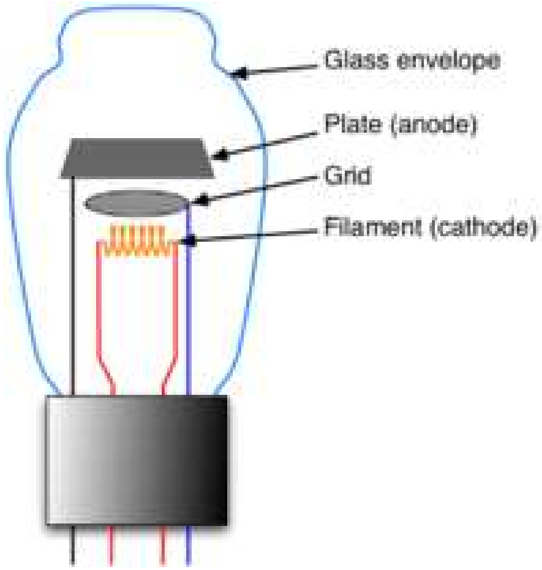
1906

- Lee De Forest -Triode in vacuum tube (**amplify** signals) allowing farther telephone conversations.

- The problems with this Triode is that it was unreliable and used a lot of power.



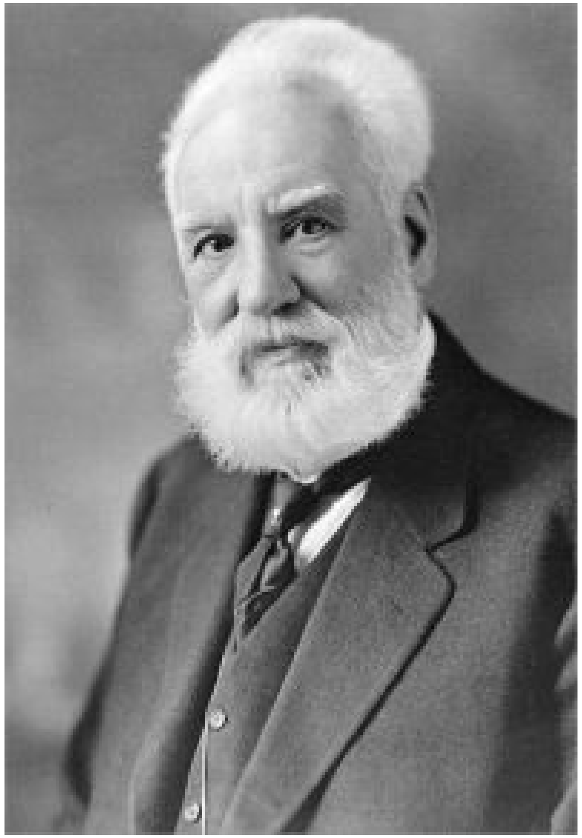
http://en.wikipedia.org/wiki/Image:Deforest.jpg



http://en.wikipedia.org/wiki/Image:Triode_vacuum_tube.png

1907

- Bell telephone patents expire.
- AT&T (Bell's company) bought De Forest's triode patent.
- Result: transcontinental telephone service.



http://en.wikipedia.org/wiki/Image:Alexander_Graham_Bell22.jpg

1928

- The first patents for the transistor principle were registered in Germany by Julius Edgar Lilienfield.

- He proposed the basic principle behind the MOS field-effect transistor

http://chem.ch.huji.ac.il/~eugeniik/history/lilienfeld.htm

1934

- German Physicist Dr. Oskar Heil patented the field effect transistor

http://www.precide.ch/eng/eheil/eheil.htm

1936

- Mervin Kelly Bell Lab's director of research. He felt that to provide the best phone service it will need a better amplifier; the answer might lie in semiconductors. And he formed a department dedicated to solid state science

http://www.pbs.org/transistor/album1/addlbios/kelly.html

1945

- Bill Shockley the team leader of the solid state department (Hell’s Bell Lab) hired Walter Brattain and John Bardeen.

- He designed the first semiconductor amplifier, relying on the field effect.
-
- His device was a small cylinder coated thinly with silicon, mounted close to a small, metal plate.

- The device didn't work, and Shockley assigned Bardeen and Brattain to find out why.

http://www.lucent.com/minds/transistor/history.html

1947

- Bardeen and Brattain built the point contact transistor.
- They made it from strips of gold foil on a plastic triangle, pushed down into contact with slab of germanium.

http://www.lucent.com/minds/transistor/history.html

http://www.lucent.com/minds/transistor/history.html

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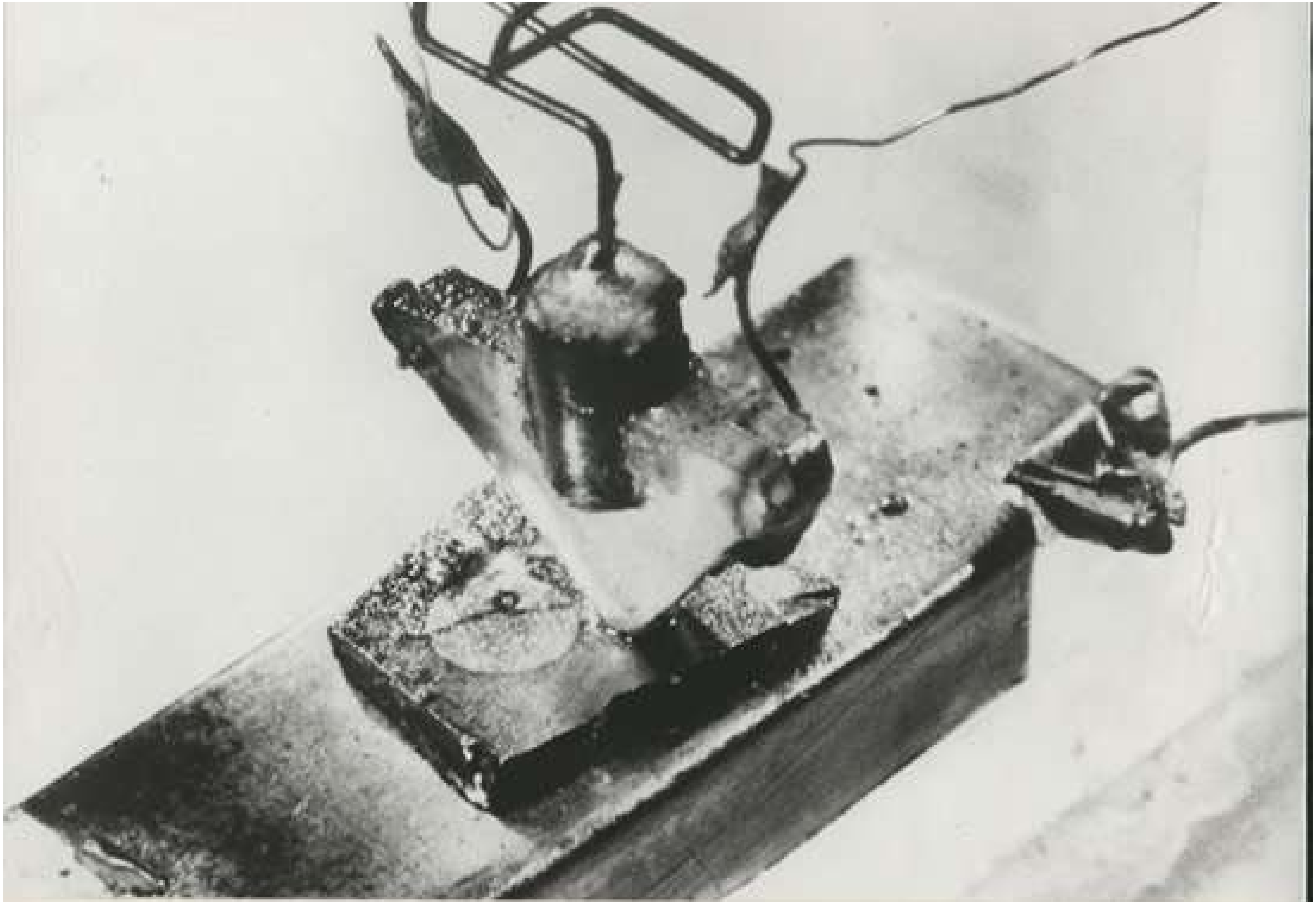
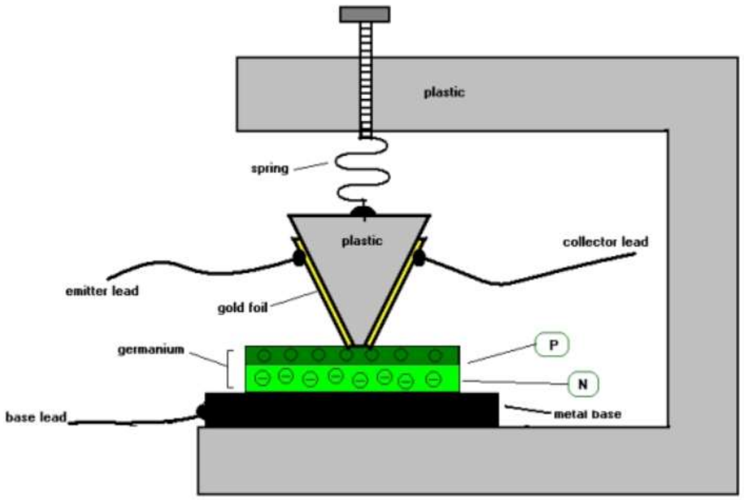
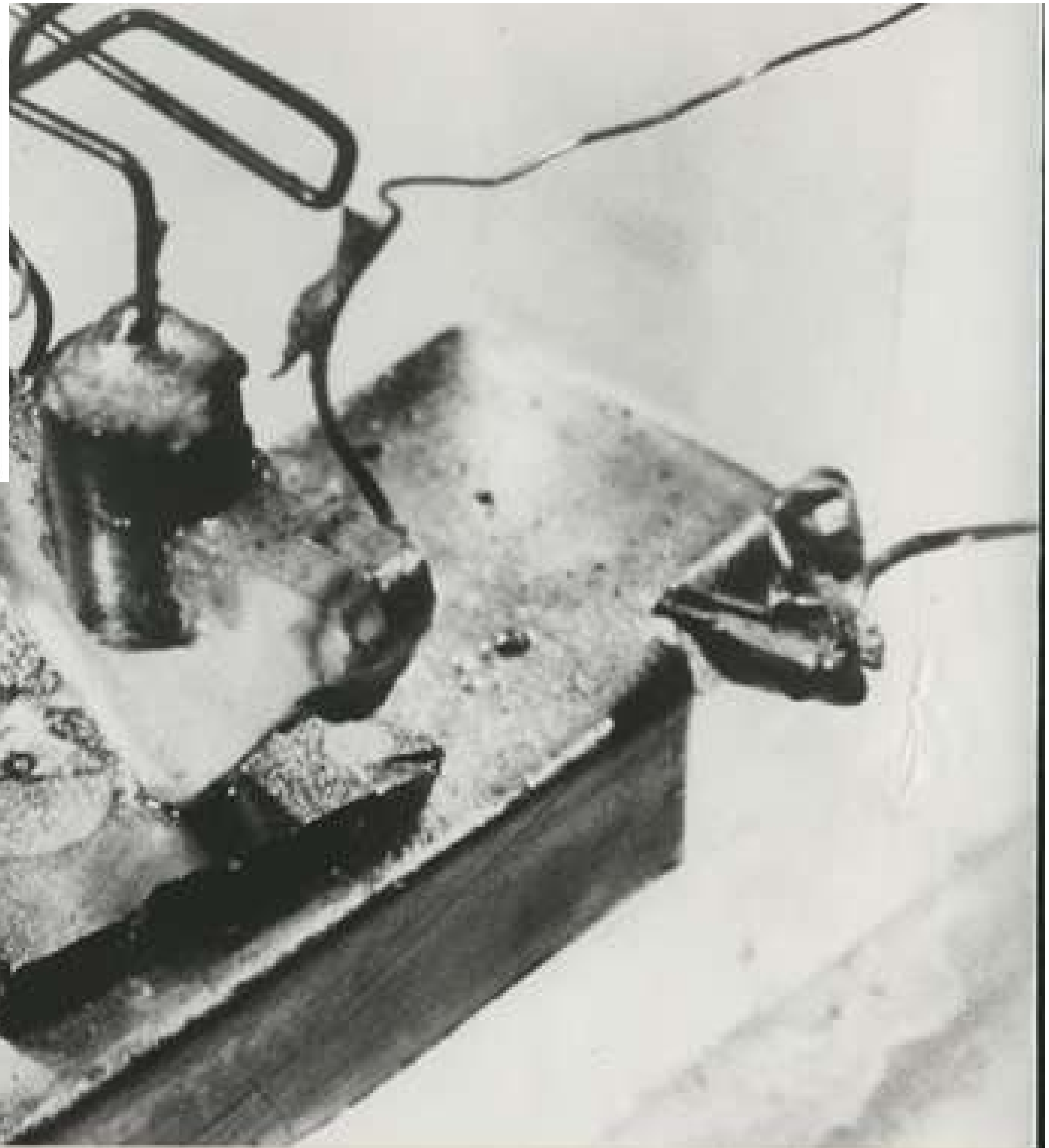


THE FIRST TRANSISTOR AS IT WAS PATENTED BY THREE NOBEL PRIZE-WINNING BELL LABORATORIES SCIENTISTS





THE FIRST TRANSISTOR AS IT WAS PATENTED BY THREE
NOBEL PRIZE-WINNING BELL LABORATORIES SCIENTISTS

The Transistor, A Semi-Conductor Triode

J. Bardeen and W. H. Brattain
Bell Telephone Laboratories, Murray Hill, New Jersey
June 25, 1948

A THREE-ELEMENT electronic device which utilizes a newly discovered principle involving a semiconductor as the basic element is described. It may be employed as an amplifier, oscillator, and for other purposes for which vacuum tubes are ordinarily used. The device consists of three electrodes placed on a block of germanium[1] as shown schematically in Fig. 1. Two, called the emitter and collector, are of the point-contact rectifier type and are placed in close proximity (separation ∼.005 to .025 cm) on the upper surface. The third is a large area low resistance contact on the base.

Phys. Rev. 74, 230

to have a positive dn/dT and is considered to have large homopolar bonding, similar reasoning predicts that $dn/d\rho$ is positive; i.e., $\lambda_0>1$. In crystals containing radicals and in many glasses, positive dn/dT values are frequently obtained although their $dn/d\rho$ values are negative. In these materials there are effects within the radical which contribute mainly to dn/dT and only slightly to $dn/d\rho$. A more complete treatment of these subjects will be presented in a forthcoming paper.

[1] H. Mueller, Phys. Rev. **47**, 947 (1935).
[2] Burstein, Smith, and Henvis, Bull. Am. Phys. Soc. **23** (2), 33 (1948).
[3] G. N. Ramachandran, Proc. Ind. Acad. Sci. **A25**, 266 (1947).
[4] S. Bhagavantam and S. Suryanarayana, Proc. Ind. Acad. Sci. **A26**, 97 (1947).
[5] C. D. West and J. Makas, Chem. Phys. **16**, 427 (1948) reported $+(p_{11}-p_{12})$ for two mixed thallium halides in agreement with our results. Their data also gives a $+(p_{11}-p_{12})$ and $-p_{44}$, for AgCl in agreement with Mueller's prediction for NaCl structures with small ratio of negative to positive ion polarizibilities. We do not agree with West and Makas concerning the sign of the diamond constants and believe them to be correct as given by Ramachandran.[3]

The Transistor, A Semi-Conductor Triode

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The germanium is prepared in the same way as that used for high back-voltage rectifiers.[2] In this form it is an N-type or excess semi-conductor with a resistivity of the order of 10 ohm cm. In the original studies, the upper surface was subjected to an additional anodic oxidation in a glycol borate solution[3] after it had been ground and etched in the usual way. The oxide is washed off and plays no direct role. It has since been found that other surface treatments are equally effective. Both tungsten and phosphor bronze points have been used. The collector point may be electrically formed by passing large currents in the reverse direction.

Each point, when connected separately with the base electrode, has characteristics similar to those of the high

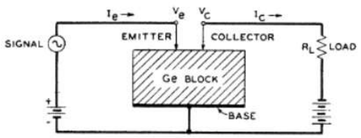


Fig. 1. Schematic of semi-conductor triode.

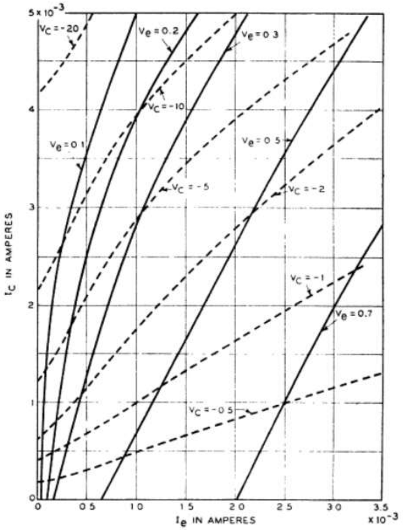


Fig. 2. d.c. characteristics of an experimental semi-conductor triode The currents and voltages are as indicated in Fig. 1.

back-voltage rectifier. Of critical importance for the operation of the device is the nature of the current in the forward direction. We believe, for reasons discussed in detail in the accompanying letter,[4] that there is a thin layer next to the surface of P-type (defect) conductivity. As a result, the current in the forward direction with respect to the block is composed in large part of holes, i.e., of carriers of sign opposite to those normally in excess in the body of the block.

When the two point contacts are placed close together on the surface and d.c. bias potentials are applied, there is a mutual influence which makes it possible to use the device to amplify a.c. signals. A circuit by which this may be accomplished in shown in Fig. 1. There is a small forward (positive) bias on the emitter, which causes a current of a few milliamperes to flow into the surface. A reverse (negative) bias is applied to the collector, large enough to make the collector current of the same order or greater than the emitter current. The sign of the collector bias is such as to attract the holes which flow from the emitter so that a large part of the emitter current flows to and enters the collector. While the collector has a high impedance for flow of electrons into the semi-conductor, there is little impediment to the flow of holes into the point. If now the emitter current is varied by a signal voltage, there will be a corresponding variation in collector current. It has been found that the flow of holes from the emitter into the collector may alter the normal current flow from the base to the collector in such a way that the change in collector

current is larger than the change in emitter current. Furthermore, the collector, being operated in the reverse direction as a rectifier, has a high impedance (10^4 to 10^5 ohms) and may be matched to a high impedance load. A large ratio of output to input voltage, of the same order as the ratio of the reverse to the forward impedance of the point, is obtained. There is a corresponding power amplification of the input signal.

The d.c. characteristics of a typical experimental unit are shown in Fig. 2. There are four variables, two currents and two voltages, with a functional relation between them. If two are specified the other two are determined. In the plot of Fig. 2 the emitter and collector currents I_e and I_c are taken as the independent variables and the corresponding voltages, V_e and V_c, measured relative to the base electrode, as the dependent variables. The conventional directions for the currents are as shown in Fig. 1. In normal operation, I_e, I_c, and V_e are positive, and V_c is negative.

The emitter current, I_e, is simply related to V_e and I_c. To a close approximation:

$$I_e=f(V_e+R_F I_c), \qquad (1)$$

where R_F is a constant independent of bias. The interpretation is that the collector current lowers the potential of the surface in the vicinity of the emitter by $R_F I_c$, and thus increases the effective bias voltage on the emitter by an equivalent amount. The term $R_F I_c$ represents a positive feedback, which under some operating conditions is sufficient to cause instability.

The current amplification factor α is defined as

$$\alpha=(\partial I_c/\partial I_e)_{V_c=\mathrm{const}}.$$

This factor depends on the operating biases. For the unit shown in Fig. 2, α lies between one and two if $V_c<-2$.

Using the circuit of Fig. 1, power gains of over 20 db have been obtained. Units have been operated as amplifiers at frequencies up to 10 megacycles.

We wish to acknowledge our debt to W. Shockley for initiating and directing the research program that led to the discovery on which this development is based. We are also indebted to many other of our colleagues at these Laboratories for material assistance and valuable suggestions.

[1] While the effect has been found with both silicon and germanium, we describe only the use of the latter.
[2] The germanium was furnished by J. H. Scaff and H. C. Theuerer. For methods of preparation and information on the rectifier, see H. C. Torrey and C. A. Whitmer, *Crystal Rectifiers* (McGraw-Hill Book Company, Inc., New York, New York, 1948), Chap. 12.
[3] This surface treatment is due to R. B. Gibney, formerly of Bell Telephone Laboratories, now at Los Alamos Scientific Laboratory.
[4] W. H. Brattain and J. Bardeen, Phys. Rev., this issue.

Nature of the Forward Current in Germanium Point Contacts

W. H. Brattain and J. Bardeen
Bell Telephone Laboratories, Murray Hill, New Jersey

June 25, 1948

THE forward current in germanium high back-voltage rectifiers[1] is much larger than that estimated from the formula for the spreading resistance, R_s, in a medium of uniform resistivity, ρ. For a contact of diameter d,

$$R_s=\rho/2d.$$

Taking as typical values $\rho=10$ ohm cm and $d=.0025$ cm, the formula gives $R_s=2000$ ohms. Actually the forward current at one volt may be as large as 5 to 10 ma, and the differential resistance is not more than a few hundred ohms. Bray[2] has attempted to account for this discrepancy by assuming that the resistivity decreases with increasing field, and has made tests to observe such an effect.

In connection with the development of the semi-conductor triode discussed in the preceding letter,[3] the nature of the excess conductivity has been investigated by means of probe measurements of the potential in the vicinity of the point.[4] Measurements were made on the plane surface of a thick block. Various surface treatments, such as anodizing, oxidizing, and sand blasting were used in different tests, in addition to the etch customarily employed in the preparation of rectifiers.

The potential, $V(r)$, at a distance r from a point carrying a current, I, is measured relative to a large area low resistance contact at the base. In Fig. 1 we have plotted some typical data for a surface prepared by grinding and etching, and then oxidizing in air at 500°C for one hour. The ordinate is $2\pi r V(r)/I$ which for a body of uniform resistivity, ρ, should be a constant equal in magnitude to ρ. Actually it is found that the ratio is much less than ρ at small distances from the point, and increases with r, approaching the value ρ asymptotically at large distances. The departure from the constant value indicates an excess conductivity in the neighborhood of the point.

The manner in which the excess conductivity varies with current indicates that two components are involved. One is ohmic and is represented by the upper curve of Fig. 1 which applies for reverse (negative) currents and for small forward currents. This component is attributed to a thin conducting layer on the surface which is believed to be P-type (i.e., of opposite type to that of the block). A layer with a surface conductivity of .002 mhos is sufficient to account for the departure of the upper curve from a constant value. The second component of the excess conductivity increases with increasing forward current, and

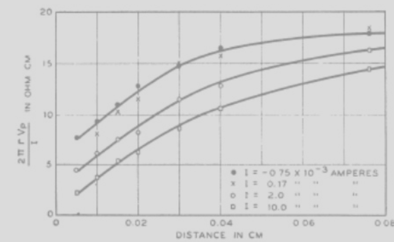
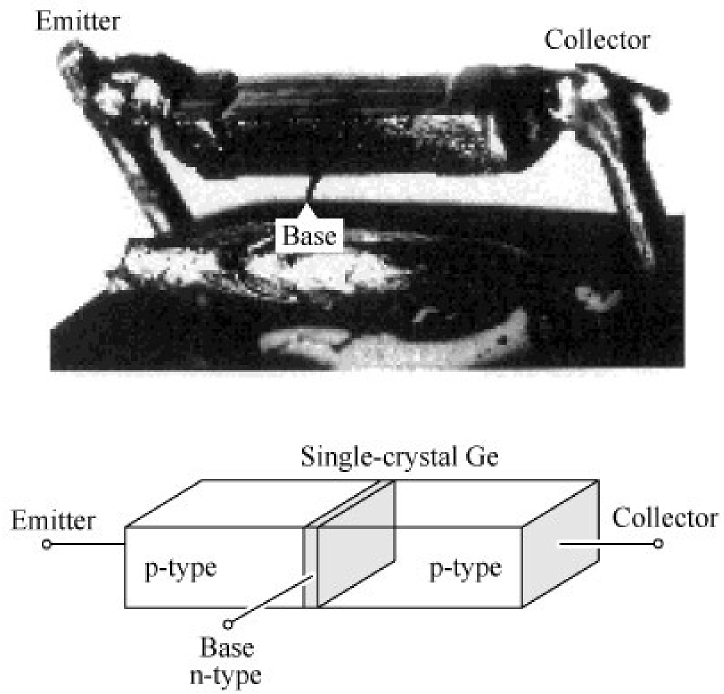


Fig. 1. Measurements of potential, V_p, at a distance r from a point contact through which a current I is flowing into a germanium surface.

1947 cont.

- Shockley make the Junction transistor (sandwich).
- This transistor was more practical and easier to fabricate.
- The Junction Transistor became the central device of the electronic age

The First Junction Transistor
First transistor with diffused pn junctions by *William Shockley*
Bell Laboratories, Murray Hill, New Jersey (1949)



http://www.ecse.rpi.edu/Homepages/schubert/Unused%20stuff/Educational%20resources/
Picture%20First%20junction%20transistor.jpg

The Theory of *p-n* Junctions in Semiconductors and *p-n* Junction Transistors

By W. SHOCKLEY

In a single crystal of semiconductor the impurity concentration may vary from *p*-type to *n*-type producing a mechanically continuous rectifying junction. The theory of potential distribution and rectification for *p-n* junctions is developed with emphasis on germanium. The currents across the junction are carried by the diffusion of holes in *n*-type material and electrons in *p*-type material, resulting in an admittance for a simple case varying as $(1 + i\omega\tau_p)^{1/2}$ where τ_p is the lifetime of a hole in the *n*-region. Contact potentials across *p-n* junctions, carrying no current, may develop when hole or electron injection occurs. The principles and theory of a *p-n-p* transistor are described.

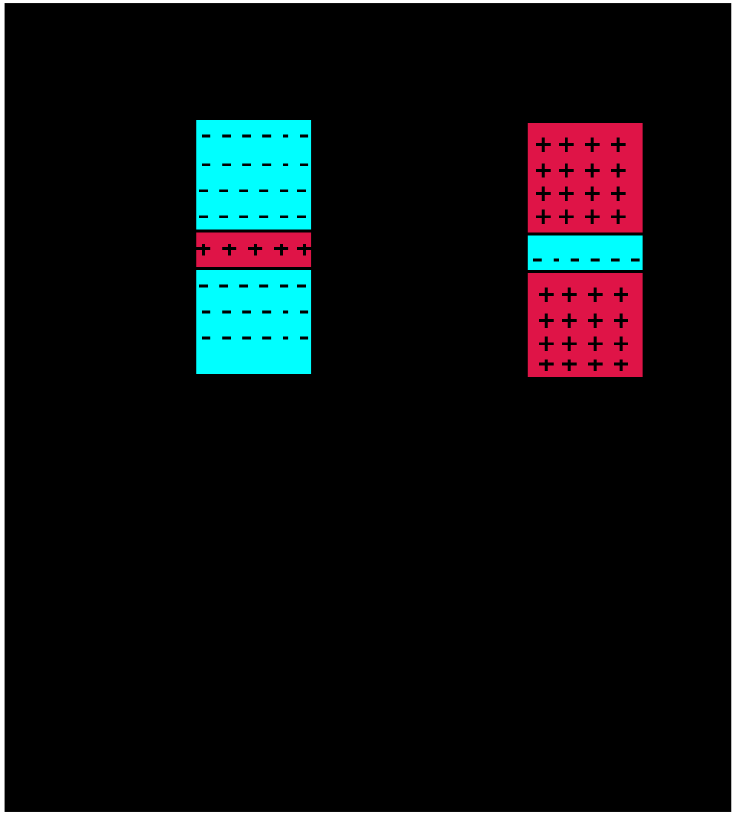
TABLE OF CONTENTS

1947 cont.

- A thin piece of semiconductor of one type between two slices of another type, is able to control the flow of the current between emitter and the collector.

- Even if the input current is weak, the transistor can control a strong current.

- The effect accomplish is that the current through the collector mimics and amplify the behavior of the current through the Emitter.



1948

- Bells Lab unveil the transistor.
- They decided to name it transistor instead of Point-contact solid state amplifier.
- John Pierce invented the name, combining transresistance with the ending common to devices, like varistor and thermistor.

1950's

- Sony receives a license from Bell Labs to build transistors
- In 1946 Sony produced products for radio repair. In 1950 they decided to build something for the mass consumption; the transistor radio.
- In United States they used the transistors primarily for computers and military uses.

http://www.sony.net/Fun/SH/1-6/h2.html

1955

- Foundation of Shockley Semiconductor, sowing the seeds of silicon valley

http://en.wikipedia.org/wiki/Image:SJPan.jpg

http://en.wikipedia.org/wiki/Image:ShockleyBldg.jpg

1957

- The traitorous eight abandoned Shockley founding Fairchild Semiconductor.

From left to right: Gordon Moore, C. Sheldon Roberts, Eugene Kleiner, Robert Noyce, Victor Grinich, Julius Blank, Jean Hoerni and Jay Last. (1960)

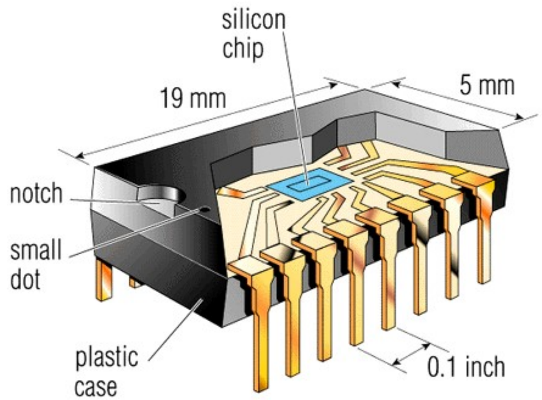
1958

- Jack Kilby of Texas Instruments – Invent the Integrated Circuit (IC)
  - It occurred to him that all parts of a circuit could be made out of the same piece of silicon.
  - The entire circuit could be built out of a single crystal
    - Reducing the size
    - Easier to produce

Texas Instruments' first IC

1958 cont. - Integrated Circuit

- A single device that contains an interconnected array of elements like transistors, resistors, capacitors, and electrical circuits contained in a silicon wafer.



http://www.helicon.co.uk/online/datasets/samples/education/images.htm

http://www.ece.uiuc.edu/grad/7reasons/5reputation.html

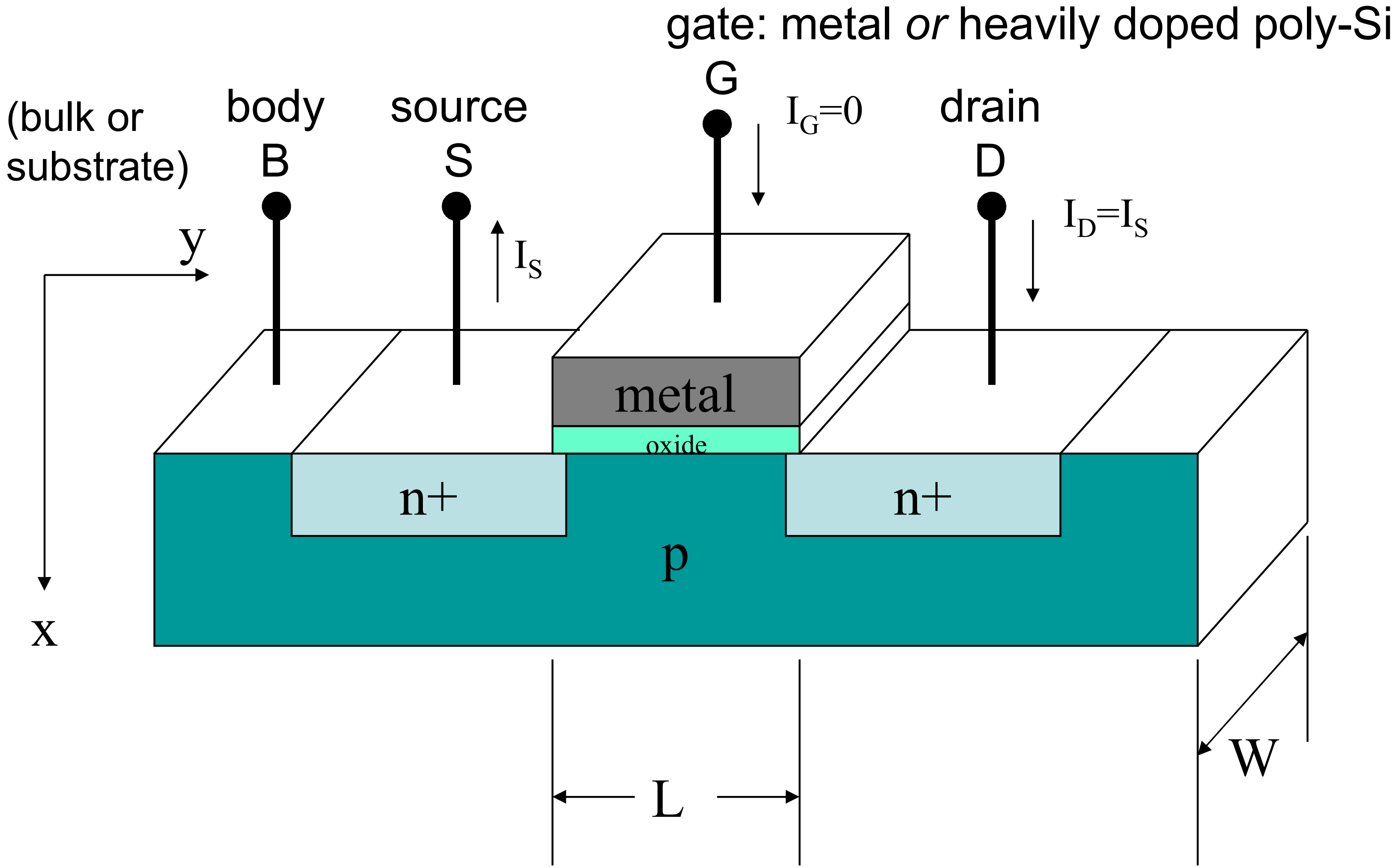
1968

- Bob Noyce and Gordon Moore, two of the traitorous eight together with Andy Grove, form Intel Corporation

http://www.itnews.sk/buxus_dev/images/2006/Intel_logo_nove1_velky.jpg

http://www.granneman.com/techinfo/background/history/

Structure: *n-channel* MOSFET (NMOS)



How a Transistor Works

- The transistor can function as:
  - An insulator
  - A conductor
- The transistor's ability to fluctuate between these two states that enables to switch or amplify.
- The transistor has many applications, but only two basic functions: switching and modulation (amplification).
- In the simplest sense, the transistor works like a dimmer.
  - With a push the knob of the dimmer, the light comes on and off. You have a switch. Rotate the knob back and forth, and the light grows brighter, dimmer, brighter, dimmer. Than you have a modulator.

How a Transistor Works cont.

- Both the dimmer and the transistor can control current flow.
- Both can act as a switch and as a modulator/amplifier.
- The important difference is that the “hand” operating the transistor is millions of times faster.

http://www.ieicorp.com/consum/dimmer.gif