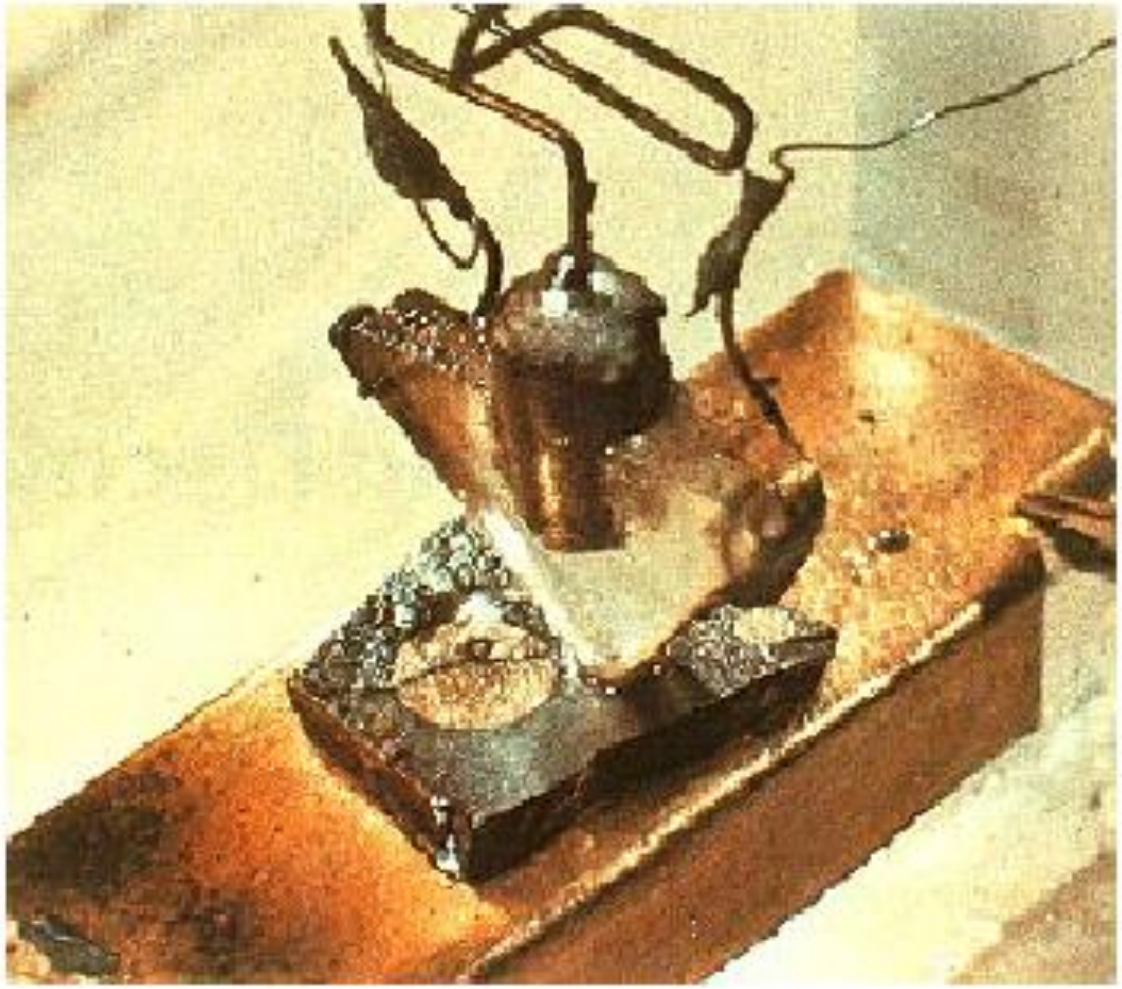
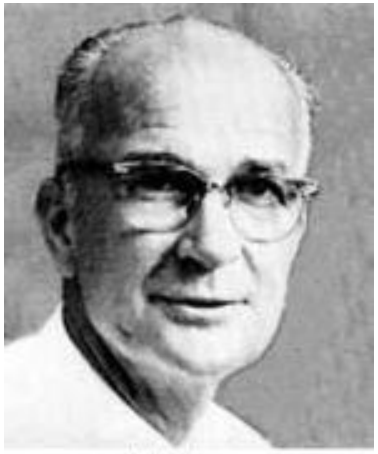
第五讲　划时代的工作---晶体管的诞生



一、晶体管的诞生


肖克莱, W. B.

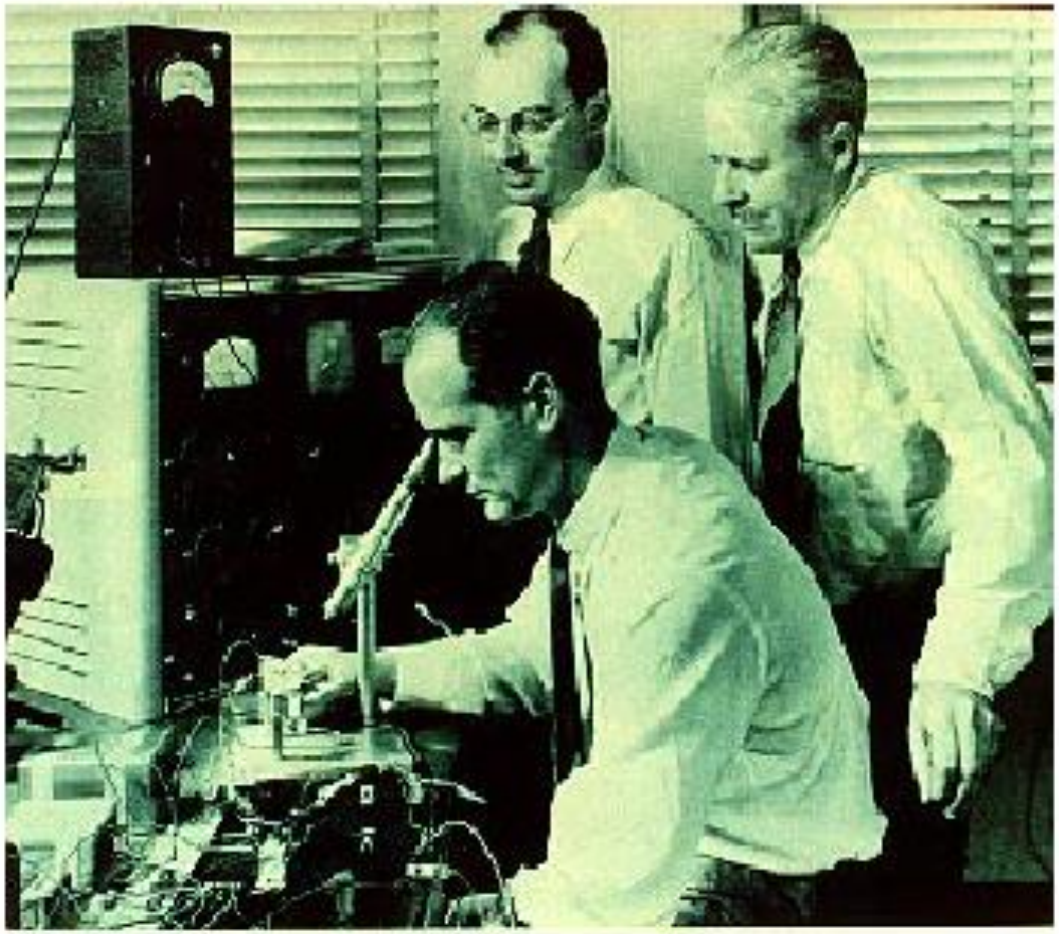
由于存在着用固体放大器代替真空三极管这一想法，1945年夏，肖克莱提出开展半导体基础研究的建议，1945年下半年，贝尔实验室成立了以肖克莱为组长的固体物理学研究小组。

在这小组里，不仅有物理学家，也有电路工程师和化学家，包括作为理论物理学家的巴丁和实验物理学家布莱顿。

真正的交叉合作团队，黄金组合

一、晶体管的诞生

第一个晶体管的诞生



John Bardeen and Walter Brattain at Bell Laboratories constructed the first solid-state transistor. This PNP point-contact germanium transistor operated with a power gain of **18 on Dec. 23, 1947**.

一、晶体管的诞生

The Transistor, A Semi-Conductor Triode

J. Bardeen and W. H. Brattain
Bell Telephone Laboratories, Murray Hill, New Jersey
June 23, 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.

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 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 is 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 impedance 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

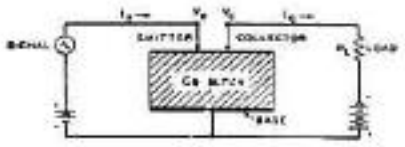


Fig. 1. Schematic of semi-conductor triode.

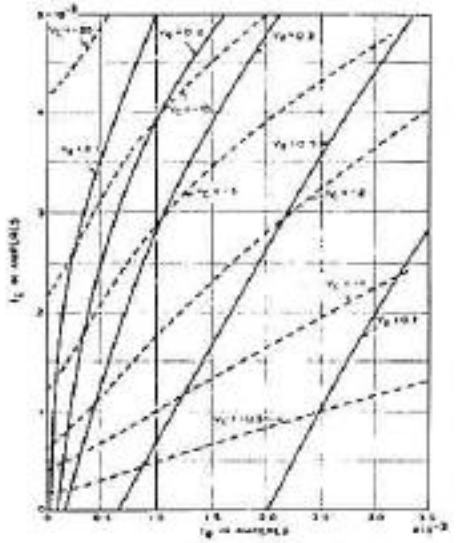


Fig. 2. d.c. characteristics of an experimental semi-conductor triode. The currents and voltages are as indicated in Fig. 1.

巴丁和布莱顿将他们的结果于1948年发表在刊登具有基础科学重要性的 《Physical Review》 上 (而不是器件或者应用物理刊物上，因为他们，应该主要是巴丁，认为点接触的原理更为重要）。

J. Bardeen and W. H. Brattain, "The Transistor, a Semiconductor Triode." Physical Review, Vol. 74 (July 15, 1948), pp. 230-231;

一、晶体管的诞生

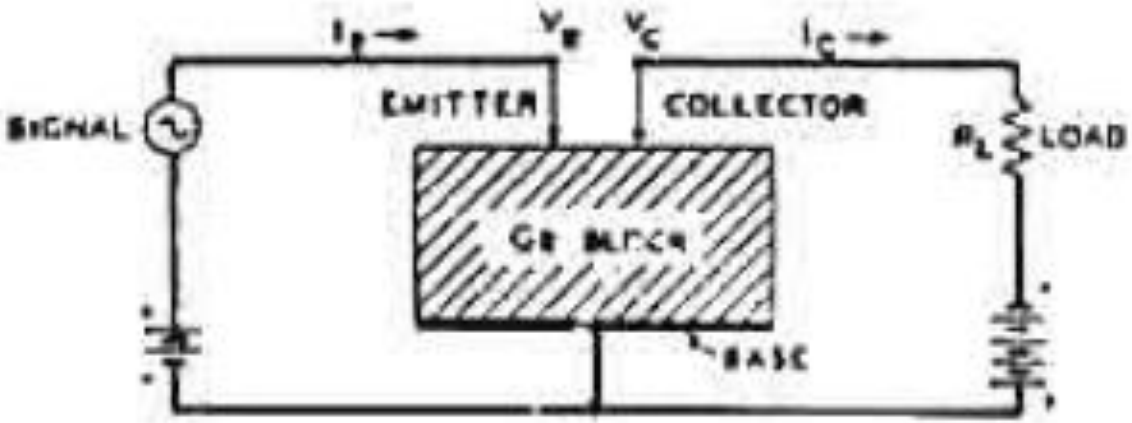


Fig. 1. Schematic of semi-conductor triode.

现在，我们已很熟悉这篇文章里对各个电极的命名，分别称为发射极，基极和集电极。发射极-基极电路中的小信号电压调制了集电极电流I_C，适当选择负载R_L，可以让输出信号远大于输入信号。

二、结型晶体管及其它

在点接触晶体管发明后，肖克莱的心情是矛盾而又复杂的。他认为巴丁和布莱顿的发明是给贝尔实验室的一个”magnificent Christmas present”，但又因为自己在里面没有起到关键角色而有失落感。

“My elation with the group’s success was tempered by not being one of the inventors,” he recalled a quarter century later. “I experienced frustration that my personal efforts, started more than eight years before, had not resulted in a significant inventive contribution of my own.“

--- Shockley, 1976

二、结型晶体管及其它

点接触晶体管的发明是一个具有划时代意义的工作，但从实用性考虑，还有许多事情远未解决。特别是真正器件应用时必须满足的可靠性和一致性问题。

贝尔实验室成立了新的团队来实现晶体管的工业化。而肖克莱将巴丁和布莱顿撂在一边，和其他人开始发展他认为更有商业价值的晶体管。肖克莱认为在点接触晶体管中，表面效应并不是主要的，而是注入的载流子可以扩散过锗材料到达电极。

二、结型晶体管及其它

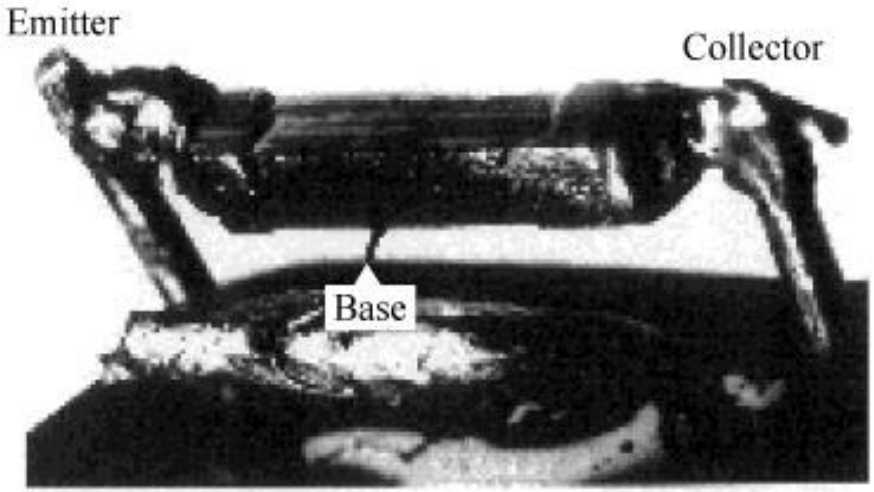
肖克莱提出了晶体管可以由两个pn结构成，一个正向偏置，作为发射极，另一个反向偏置，作为集电极的构想。

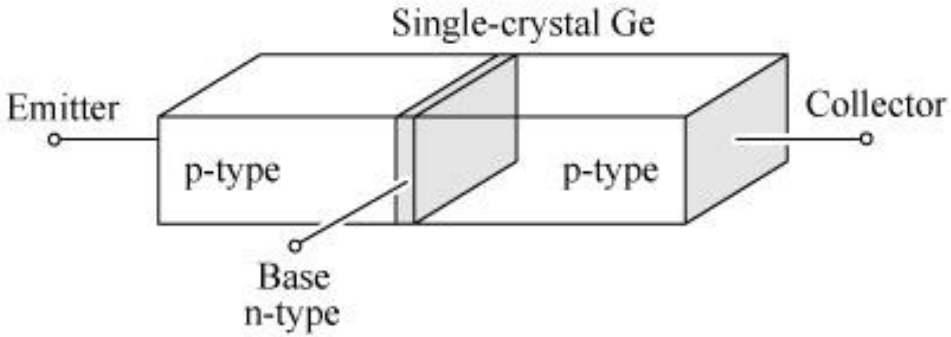
制作时可以利用两个p型层中间夹一n型层作为半导体放大结构，这样可以很好地解决金属点接触重复性差的问题，并且是一个一维器件结构，可以很容易地进行建模计算。很快，肖克莱与M．Sparks和G．K．Teal一起发明了单晶锗NPN结型晶体管。

二、结型晶体管及其它

The First Junction Transistor

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





二、结型晶体管及其它

The Nobel Prize in Physics 1956

William Bradford Shockley
Prize share: 1/3

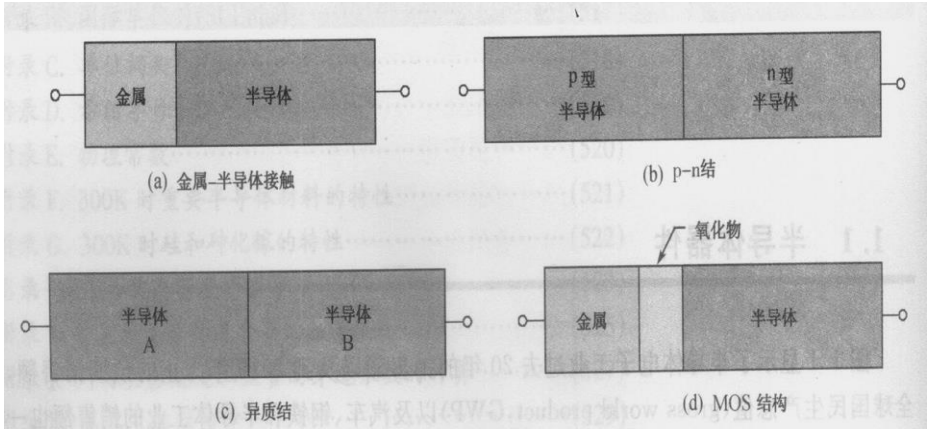
John Bardeen
Prize share: 1/3

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".*

二、结型晶体管及其它

虽然半导体器件种类繁多，但均可划分为几种基本的器件结构：



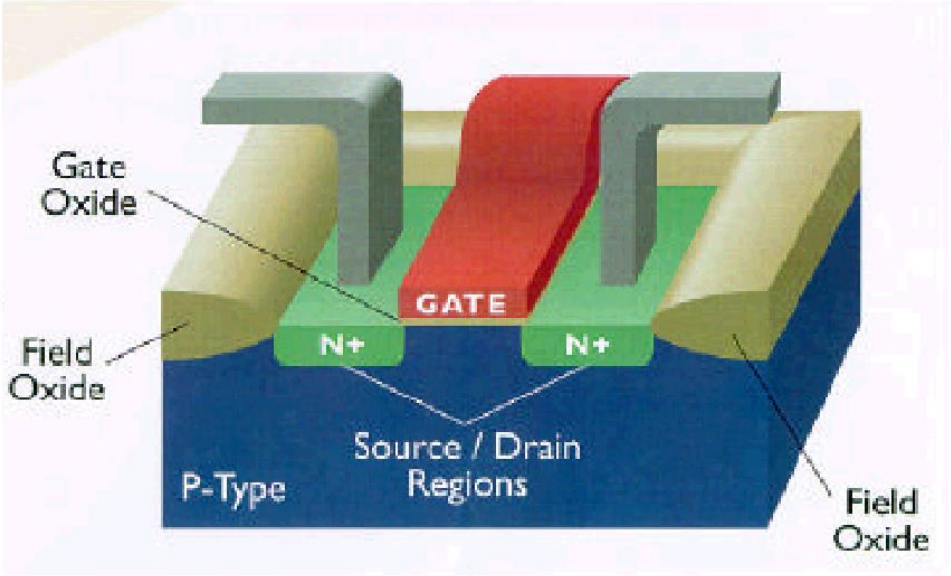
金属-半导体：
整流接触/欧姆接触-
金半场效应晶体管；

p-n结：
是大部分半导体器件的关键基本结构-pnp双极型晶体管，可控硅器件，太阳能电池；

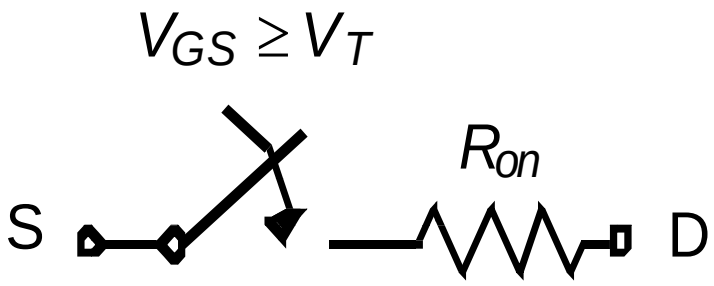
异质结：
III-V族半导体器件的基本结构-快速器件，光电器件；

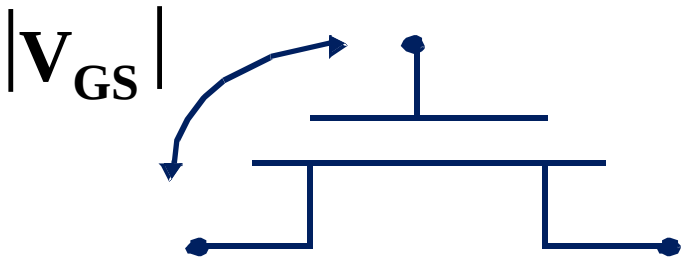
MOS结构：
集成电路中最重要的器件结构-MOSFET;

二、结型晶体管及其它



an MOS Transistor





a Switch!

三、Lilienfeld的构想

Lilienfeld FET Transistor (1930)

J. E. Lilienfeld, who obtained several concept patents on a field-effect transistor nearly twenty years before the work on the transistor started at the Bell Telephone Laboratories. The patents created interference with Shockley's application. The photograph is taken from Lilienfeld's U.S. naturalization documents. (Reprinted with permission from *Physics Today* [May 1988]: 87. © 1988 American Institute of Physics.)

三、Lilienfeld的构想

Julius Edgar Lilienfeld (1882-1963)：德国人，曾在University of Leipzig任教，后由于德国日益增长的迫害犹太人的形式而移居美国，是公司的电容工程师。 他于 1925年第一个提出了场效应晶体管的概念并于1930年获得专利。

1935年，Oskar Heil描述了一种类似于结型场效应晶体管的结构 (O. Heil, British Patent 439,457, 1935).

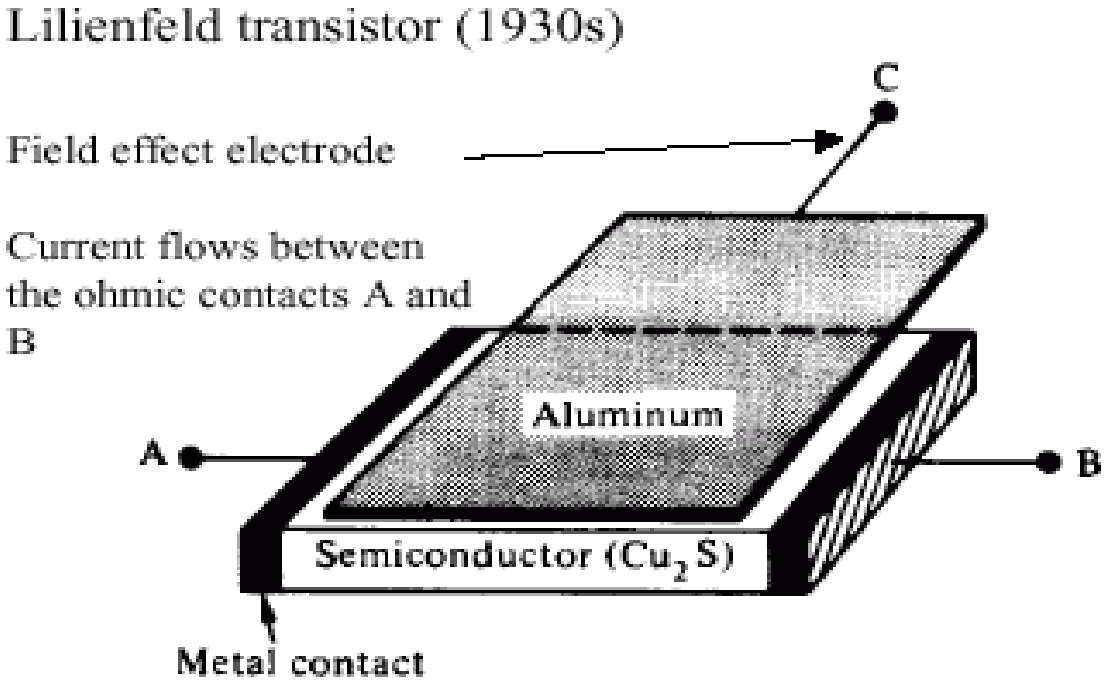
三、Lilienfeld的构想

Lilienfeld could not build FET because of excessive surface states at the interface between the oxide and the semiconductor. Charges were so numerous that current flowed with zero bias. It was only possible to turn OFF the device by driving the carriers deep (now called a "depletion mode" FET). Charges were such that only n-type semiconductors could be used. During the 1950s, methods reduced the surface states and enable the fabrication of a normally OFF device with zero bias, "enhancement-mode" FET. The first working MOS-FET was announced in 1960 (ATT).

Now, most MOS-FETs are "enhancement - mode" devices made on p-type silicon.

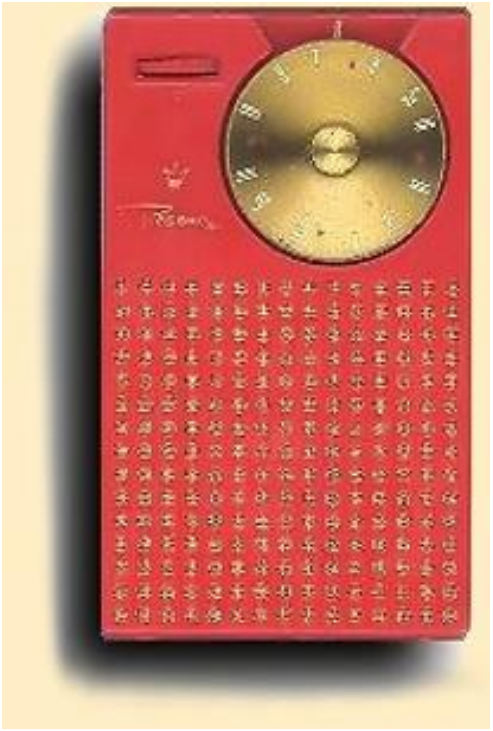
三、Lilienfeld的构想

虽然由于材料制备的实际困难，Lilienfeld的晶体管在当时是不可能的做出来的。但由于有这个专利在先，Shockley最初的场效应晶体管的专利申请被完全驳回；Bardeen的点接触晶体管的专利也因此而有超过半数的人认为不能通过。



四、日本企业的崛起

随着晶体管的诞生，晶体管收音机也随即代替了电子管收音机走进人们的生活。



世界上第一个晶体管收音机是由Regency公司研制出来的TR-1收音机。

The first transistor radio was a joint project of the Regency Co. and Texas Instruments. TI built the transistors; Regency built the radio. It hit the consumer market on October 18, 1954. It was a scant five inches high, the unit weighed eleven ounces and cost $49.95.

四、日本企业的崛起

The Regency TR-1 featured four germanium transistors operating on a 22.5-volt battery that provided over twenty hours of life. It was discontinued in 1955.

四、日本企业的崛起

In Japan, a tiny company had other ideas. **Tsushin Kogyo （通信工业）** was close to manufacturing its first radios when it heard that an American company had beaten them to market. But they persevered and made a radio, the TR-52. When Regency quit producing their radio, the Japanese company immediately started shipping their radio to the U.S.

四、日本企业的崛起

One immediate problem was that Americans couldn’t pronounce their name. The founders, Ibuka（井深大） and Morita（盛田昭夫）, thought of using a Latin word **sonus** meaning "*sound*." Akio Morita knew some English, and made a simple variation that became their name from then on:

Sony“是由表示声音的拉丁文词根”sonus“和含义为”聪明可爱“的”sonny“两个词组成而来的。公司原名“东京通信工业株式会社”，

四、日本企业的崛起

夏普成立于1912年，公司原称“早川电机工业”，是由早川德次在日本东京创立的，产品是自动铅笔，品牌是“Ever-Sharp Pencil”，取其“不用削，可永保笔芯尖锐”的意思。SHARP的商标就是来自于此。

早川德次（1893—1980），早年生活十分贫困，只读到小学二年级，但最终成为日本夏普公司创始人。

四、日本企业的崛起

在得知晶体管诞生的消息后，早川敏锐地感到晶体管和集成电路的优势。率先在世界上开发了基于晶体管的电子计算器**Sharp *QT-8D "micro Compet"***。

Sharp *QT-8D "micro Compet"*

Display is 8 digits, green vacuum fluorescent "Itron" tubes.
Size: 245 x 132 x 70 mm. (9.6" x 5.2" x 2.75").

四、日本企业的崛起

Sharp were pioneers in the field of calculator electronics and had a collaboration agreement with Rockwell to develop Large-Scale Integration (LSI) integrated circuits for calculators, thereby greatly reducing the component count. They were first used in the AC powered QT-8D of late 1968 .

夏普公司在1963年领先于其他公司实现了实用化的太阳能发电；1973年，实现了液晶实用化，制作出了液晶显示计算器。

包括其它的一些日本公司都抓住了半导体发展的机遇，使得日本半导体企业在国际上崛起，至今仍有着巨大的影响。

第五讲　结语

"Without the invention of the transistor, I'm quite sure that the PC would not exist as we know it today"

--- Bill Gates

"....the story not only of one of the greatest inventions of the 20th century but of the birth of the information age."

--- PHYSICS TODAY book review of CRYSTAL FIRE, the history of the transistor