# 传奇半导体

## The LEGEND OF SEMICONDUCTORS


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# 背景介绍

## 参考资料：

- Semiconductor Devices: Pioneering Papers, S. M. Sze;
- History of Semiconductor Research, G. L. Pearson and W. H. Brattain, Proceedings of the IRE,1955；
- 半导体物理学，刘恩科、朱秉升、罗晋生等；
- 半导体的故事，约翰·奥顿著，姬扬译；
- 固体物理引论，C. Kittel；
- 半导体器件物理与工艺，施敏；

# 背景介绍

**课程安排**：

每周一次讲课

**总课时: 12x2= 24学时**

**课程内容:** 一共十讲，以课堂讲授和课堂探讨为主。课后留有研讨课题，也请同学踊跃报名上台报告；

**考核依据:** 平时课堂问答及研讨报告情况

期末报告和其它

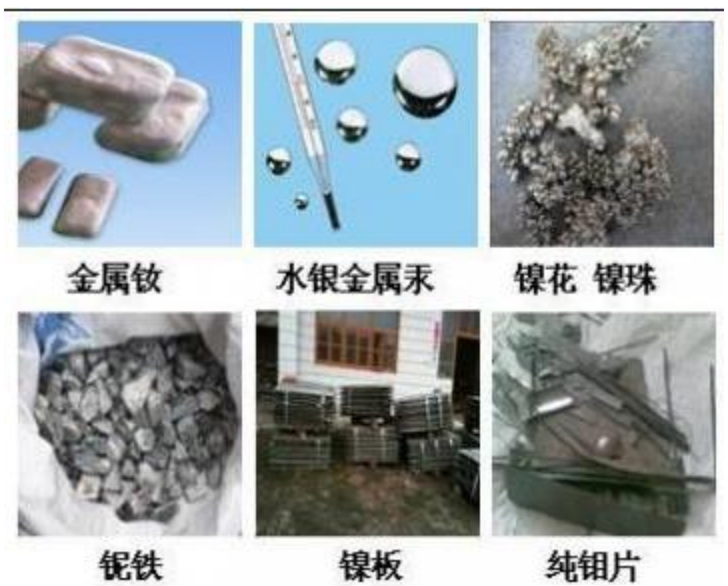
(要求在整个授课过程中要完成至少两篇课后研讨报告，在课程结束时提交课程期末报告)

# 第一讲　引言-什么是半导体

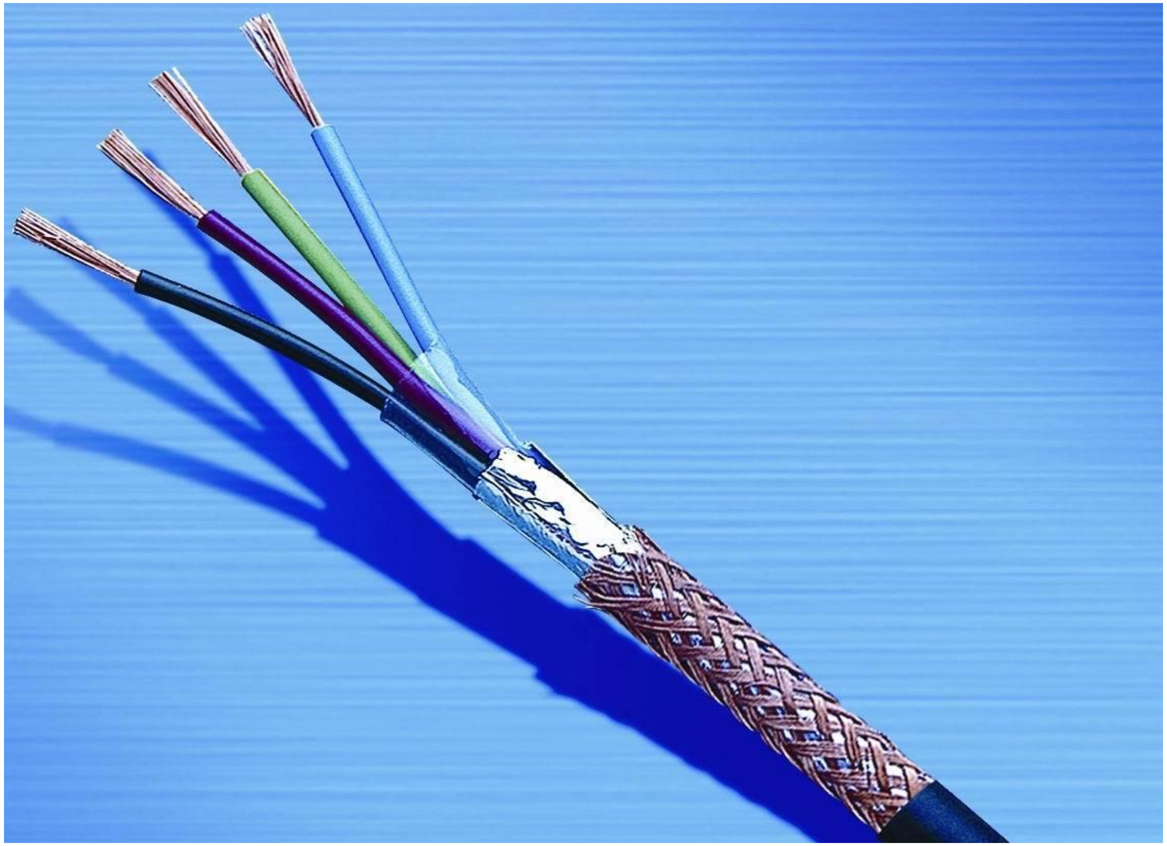
## 半导体 --- Semiconductor

Semiconductors are defined by their unique electric conductive behavior, somewhere between that of a metal and an insulator.

--- *Yu, Peter (2010). Fundamentals of Semiconductors. Berlin: Springer-Verlag.* *ISBN 978-3-642-00709-5*

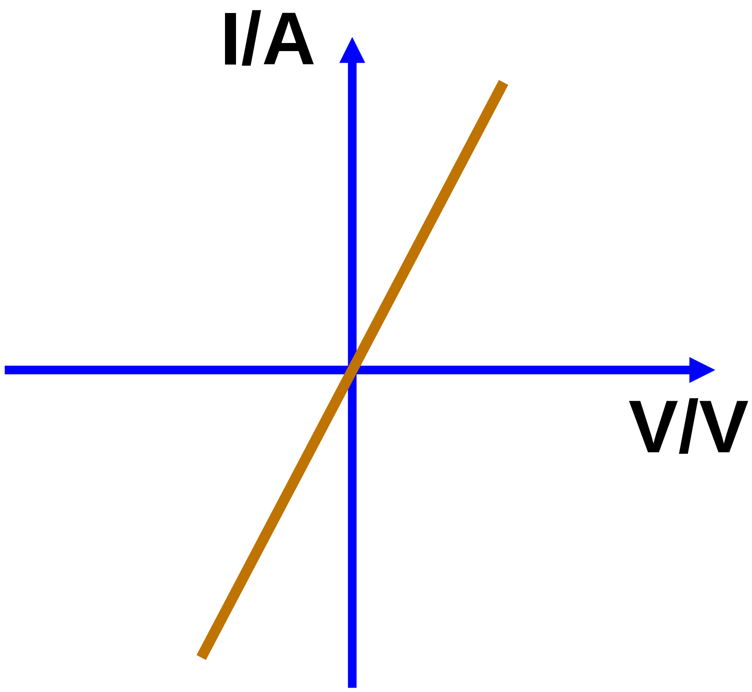



# 金属和绝缘体
# --- Metal (Conductor) and Insulator



# 一、电阻率和电导率

- 欧姆定律




对于金属，
电流 I = V(电压) /R (电阻)

V-I关系是直线

而电阻：
$R=\rho l/s$，

其中 ρ是电阻率，
单位是 Ω•cm

## 一、电阻率和电导率

对于半导体，流过不同截面的电流强度不一定相同，即电流分布不均匀，而欧姆定律不能说明材料内部各处电流的分布情况。

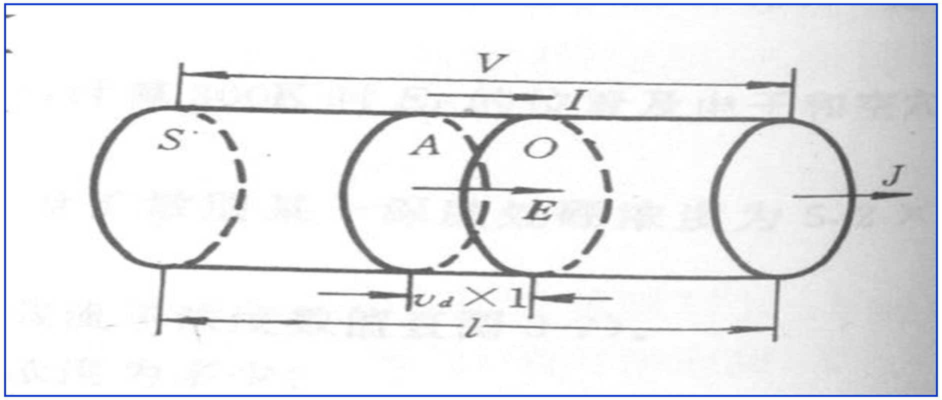
**电流密度：**

通过垂直于电流方向的单位面积的电流

$$J = \Delta I/\Delta S$$

单位： $A/cm^2$ 或 $A/m^2$

# 一、电阻率和电导率




若在如图所示的半导体两段加上电压V，

则电场强度：$E=V/L$

电流密度：$J=I/S=V/RS$

有： $$J=\frac{V}{\rho L/S \bullet S}=E/\rho$$

# 一、电阻率和电导率

引入电导率σ

**σ（电导率）＝1/ρ（1/电阻率）**

$$J = \sigma |E|$$

**这是欧姆定律微分形式**

上式把通过导体中某一点的电流密度和该处的电导率及电场强度直接联系了起来。

# 一、电阻率和电导率

**电阻率（resistivity）**是用来表示各种物质电阻特性的物理量

**电导率（conductivity ）**是用来描述物质中电荷流动难易程度的参数

Werner von Siemens (1816-1892)

**单位：**

**电导率：** $(\Omega\bullet cm)^{-1}$

**或者 S/cm;**

**电阻率：** $\Omega\bullet cm$

**S – Siemens（西门子）**

# 一、电阻率和电导率

**导体：** 电导率 》$10^3$-$10^4$ （欧姆厘米）$^{-1}$
**绝缘体：** 电导率 《$10^{-10}$ （欧姆厘米）$^{-1}$
**半导体：** 电导率介于两者之间。

| | | | |
|---|---|---|---|
| Insulators | $\sigma = 10^{-22}$ | to $10^{-13}$ | $(\Omega\ \mathrm{cm})^{-1}$ |
| Electrolytes | $\sigma = 10^{-13}$ | to $10^{-10}$ | $(\Omega\ \mathrm{cm})^{-1}$ |
| Semiconductors | $\sigma = 10^{-10}$ | to $10^{3}$ | $(\Omega\ \mathrm{cm})^{-1}$ |
| Metals | $\sigma = 1$ | to $10^{3}$ | $(\Omega\ \mathrm{cm})^{-1}$ |
| Superconductors | $\sigma > 10^{3}$ | | $(\Omega\ \mathrm{cm})^{-1}$ |

# 二、早期的半导体实验观测

在“半导体”这个概念出现之前*，其实就已经有科学家观测到了一些材料所具有的独特的特性，今天我们知道这些其实就是半导体性质。其中最重要的有四个实验观测报道**（“四大”发现）。**

** Semiconducting一词据说是Alessandro Volta最早使用。*

## 1、M. Faraday的实验观测

***Michael Faraday (1791-1867)***

*was a British chemist and physicist who contributed significantly to the study of electromagnetism and electrochemistry. In 1831, Faraday discovered electromagnetic induction, the principle behind the electric transformer and generator. This discovery was crucial in allowing electricity to be transformed from a curiosity into a powerful new technology.*

# 1、M. Faraday的实验观测

EXPERIMENTAL RESEARCHES

IN

ELECTRICITY.

BY

MICHAEL FARADAY, D.C.L. F.R.S.

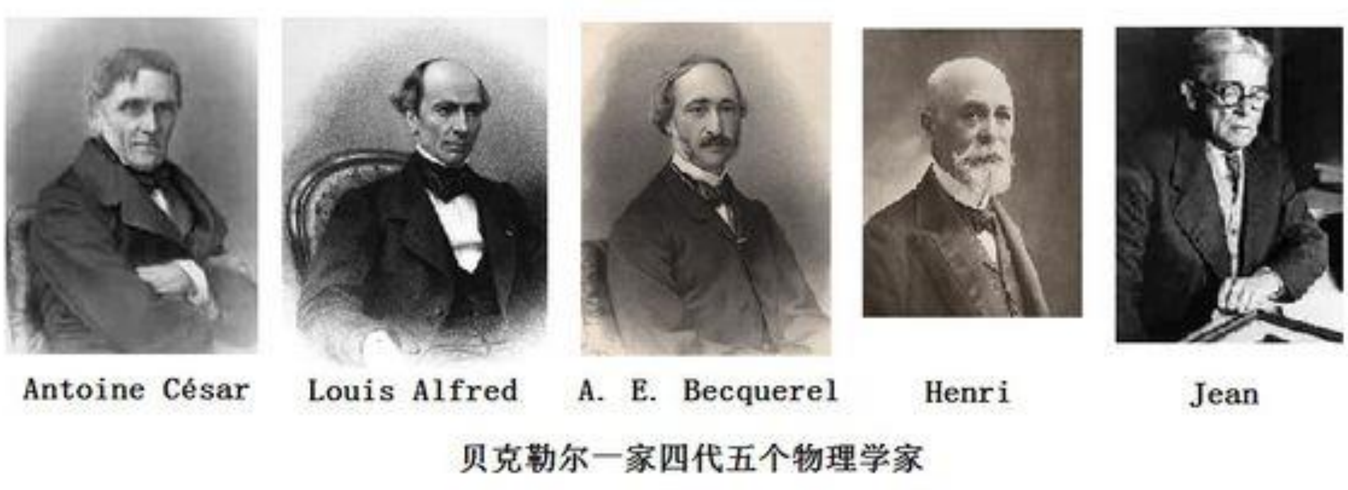
FULLERIAN PROFESSOR OF CHEMISTRY IN THE ROYAL INSTITUTION.

FOREIGN ASSOCIATE OF THE ACAD. SCIENCES, PARIS, ORD. BORUSS. POUR LE MÉRITE EQ., MEMB. ROYAL AND IMPERIAL ACADD. OF SCIENCES, PETERSBURGH, FLORENCE, COPENHAGEN, BERLIN, GOTTINGEN, MODENA, STOCKHOLM, MUNICH, BRUXELLES, VIENNA, BOLOGNA, ETC. ETC.

In 1833 he found that silver sulfide had a negative temperature coefficient of resistance. This characteristic set it apart from other conductors (metals) whose resistance increased with increase in temperature.

**半导体电阻率的负温度系数**

# 2、A. E. Becquerel的工作




1839年贝克勒尔(A. E. Becquerel)首次在液体中发现了一种效应，他用有AgCl覆盖的铂电极插在电解液中时，发现两电极间的电压会随光照强度变化的现象。

随后，在固体硒中也发现了类似的效应。

**半导体的光伏效应**

# 3、W. Smith的故事

such great differences in the resistance of the bars, it was found that the resistance altered materially according to the intensity of light to which it was subjected. When the bars were fixed in a box with a sliding cover, so as to exclude all light, their resistance was at its highest, and remained very constant, fulfilling all the conditions necessary to my requirements; but immediately the cover of the box was removed, the conductivity increased from 15 to 100 per cent. according to the intensity of the light falling on the bar. Merely intercepting the light by pass-

**半导体的光电导效应**

# 3、W. Smith的故事

PHILOSOPHICAL

TRANSACTIONS:

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## The Action of Light on Selenium

W. G. Adams and R. E. Day

*Phil. Trans. R. Soc. Lond.* 1877 **167**, 313-349, published 1 January 1877

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1876年，W. G. Adams和他的学生R. E. Day系统研究了固体硒中在光照下的各种现象。

# 4、F. Braun的重大发现

**Karl Ferdinand Braun** (1850 –1918) was a German inventor, physicist. He contributed significantly to the development of radio and television technology. ***（他是阴极射线管CRT的发明者！）***

In 1874, Braun discovered that contacts between metals and various sulfides such as galena (方铅石-硫化铅) and pyrites(黄铁矿-硫化铁）would **rectify**.

*"With a large quantity of natural and artificial metallic sulfides and greatly varying pieces, the most perfectly formed crystals that I could find, as well as coarse samples, I discovered that their resistance varied with the direction, intensity and duration of the current. The differences amount up to 30% of the total amount."*

**the resistance did not obey Ohm's law!**

**半导体的整流特性**

# 4、F. Braun的重大发现

F. Braun的发现是非常重要的，因为基于整流效应导致了最基本和简单的半导体器件二极管的诞生，也为随后一系列重要的半导体器件乃至集成电路和信息时代的到来打下了基础。

*"If device literature exhibits normal life cycle characteristics (i.e. from inception to growth, to saturation, and finally to decline), we can state that the inception phase is from 1874 (the first study of metal –semiconductor contacts) to 1947 (the invention of transistor)."*

--- S. M. Sze,

Semiconductor Devices: Pioneering Papers, World Scientific, 1991

## 三、E. Hall的工作

在1879年，对半导体物理至关重要的实验已经被报道了，这就是

**Hall效应实验**

一个24岁的年轻人的杰出工作！

# 三、E. Hall的工作

**Edwin Herbert Hall**
(1855 –1938)

1879年，Edwin Hall是美国Johns Hopkins 大学的一个年轻博士生，在罗兰教授指导下学习物理学，他在研究通有电流的金属导体在磁场中受力的情况时，发现了一种新的电磁效应，这就是霍尔效应(Hall Effect)。

***注意一个时间点，***
***电子本身是在1911年才由J. J. Thomson发现的。***

# 三、E. Hall的工作

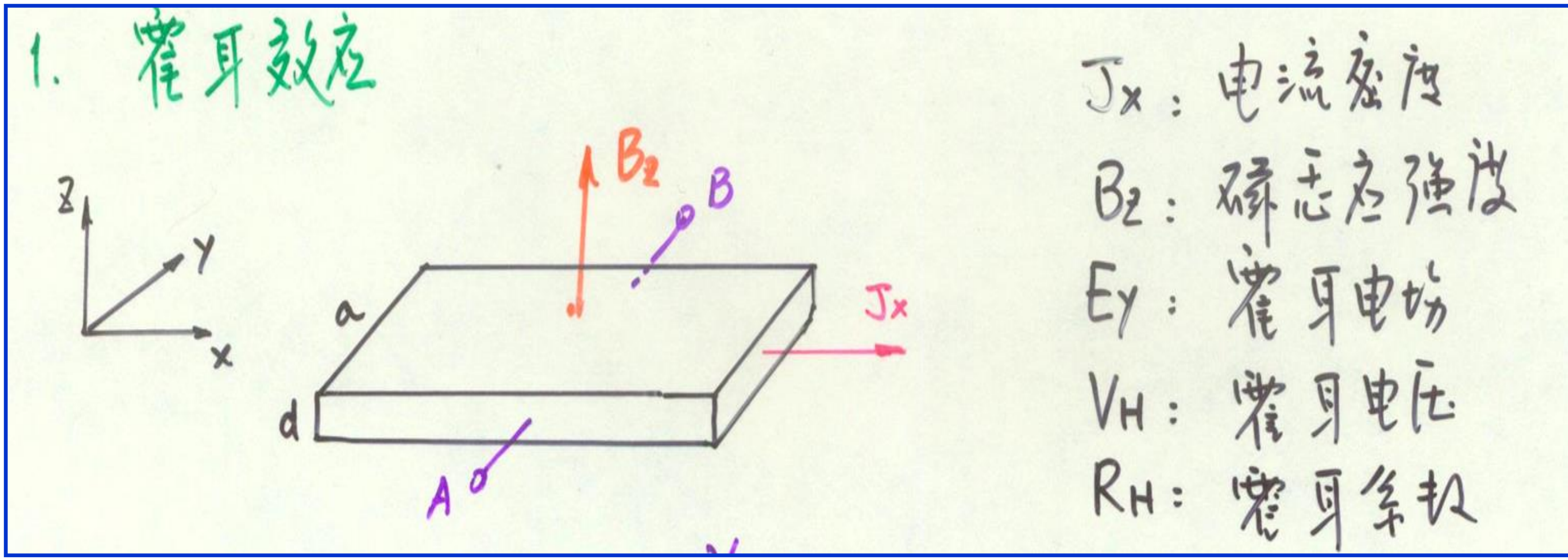
Hall设计了实验，发现如果在电流的垂直方向加上磁场，那么在垂直于磁场和电流的方向上会产生横向电动势。这个电动势和外加磁感应强度和电流密度成正比。

The transverse electromotive force E′ seems to be, under ordinary circumstances, proportional to M$v$, where M is the intensity of the magnetic field and $v$ is the velocity of the electricity in the gold leaf. Writing for $v$ the equivalent expression $\frac{C}{s}$ where C is the primary current through a strip of the gold leaf 1 cm. wide, and $s$ is the area of section of the same, we have $E' \propto \frac{MC}{s}$.

*--- E. H. Hall, American Journal of Mathematics Vol. 2 (1879), pp. 287-291.*

# 三、E. Hall的工作

设电场沿x方向,电场强度为Ex，
磁场方向和电场垂直，沿z方向，磁感应强度为Bz，在垂直于电场和磁场的+y和-y方向产生的横向电场为$E_y$，

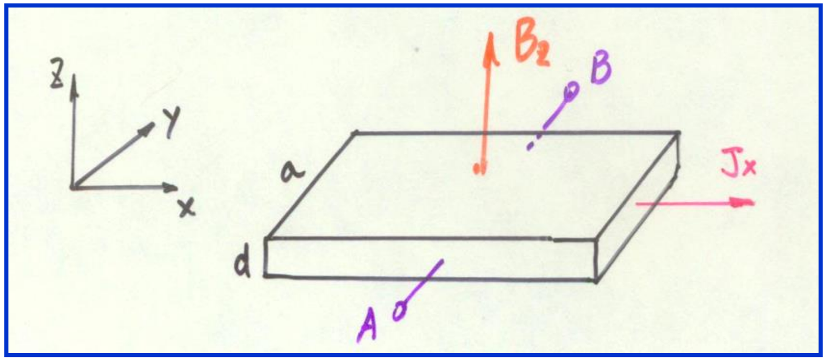



$$E_y = V_H/a = R_H J_x B_z$$

$$R_H = E_y/J_xB_z = V_H/a\, J_x B_z = V_H\, d/I_x B_z$$

***$R_H$称为霍尔系数，可以直接测得！***

# 三、E. Hall的工作




**霍尔系数符号的困惑**

考虑到电流是带负电荷的载流子导致的，所以Hall电场的方向应该指向负y轴，因此**霍尔系数应该是负的。**

在Hall效应发现后，人们对不同的材料进行了研究，

发现对于金属来说，确实霍尔系数符号为负，复合预期；

但在某些材料中（像氧化亚铜），人们观测到了正的霍尔系数，这意味着有带正电荷的载流子；

有的时候霍尔系数会随着温度变化而变号；

## Pre-1900 Research

- **Negative temperature coefficient of resistance;**
- **Photoconductivity;**
- **Rectification;**
- **Photoelectric conversion;**
- **Hall effect**

但对以上现象的物理本质，仍存在争议，是本征的性质，还是杂质引起的，还是热效应，还是表面和界面的问题?

**对以上问题的认识需要等待量子力学和固体物理的发展...**

# 第一讲　结语

*The history of semiconductor research is a very interesting story...*

*Semiconductor research began quite inconspicuously about 120 years ago with some observations on the electrical properties of silver suphide. Progress was very slow for the next 50 years and then...*

**---G. L. Pearson and W. H. Brattain**
**"History of Semiconductor Research"，**
**Proceedings of the IRE,1955**