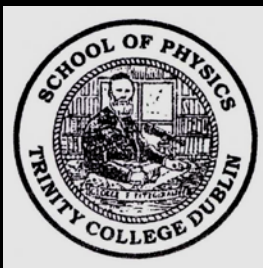
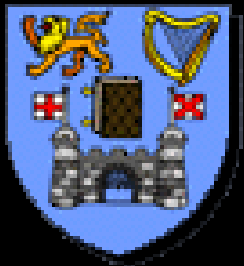


Semiconductor Devices - 2014

Lecture Course
Part of
SS Module PY4P03

Dr. P. Stamenov

School of Physics and CRANN, Trinity College,
Dublin 2, Ireland



Hilary Term, TCD
14th of Feb '14



The Esaki Diode

Now SONY

NATURE|Vol 464|4 March 2010

Esaki diode is still a radio star, half a century on

An FM transistor radio owned by one of us (L. E.) since the early 1960s still works beautifully. Reasoning that this was testament to the performance of its single Esaki diode, we tested the effects of storage on some of these germanium devices made in 1960.

Phys. Rev. **109**, 603–604 (1958) →

New Phenomenon in Narrow Germanium p - n Junctions

LEO ESAKI

Tokyo Tsushin Kogyo, Limited, Shinagawa, Tokyo, Japan

(Received October 11, 1957)

IN the course of studying the internal field emission in very narrow germanium p - n junctions, we have found an anomalous current-voltage characteristic in the forward direction, as illustrated in Fig. 1. In this p - n junction, which was fabricated by alloying techniques, the acceptor concentration in the p -type side and the donor concentration in the n -type side are, respectively, $1.6 \times 10^{19} \text{ cm}^{-3}$ and approximately 10^{19} cm^{-3} . The maximum of the curve was observed at 0.035 ± 0.005 volt in every specimen. It was ascertained that the specimens were reproducibly produced and showed a general behavior relatively independent of temperature. In the range over 0.3 volt in the forward direction, the current-voltage curve could be fitted almost quantitatively by the well-known relation: $I = I_s [\exp(qV/kT) - 1]$. This junction diode is more conductive in the reverse direction than in the forward direction. In this respect it agrees with the rectification direction predicted by Wilson, Frenkel, and Joffe, and Nordheim 25 years ago.¹

The Tunnel Diode – IV Characteristics

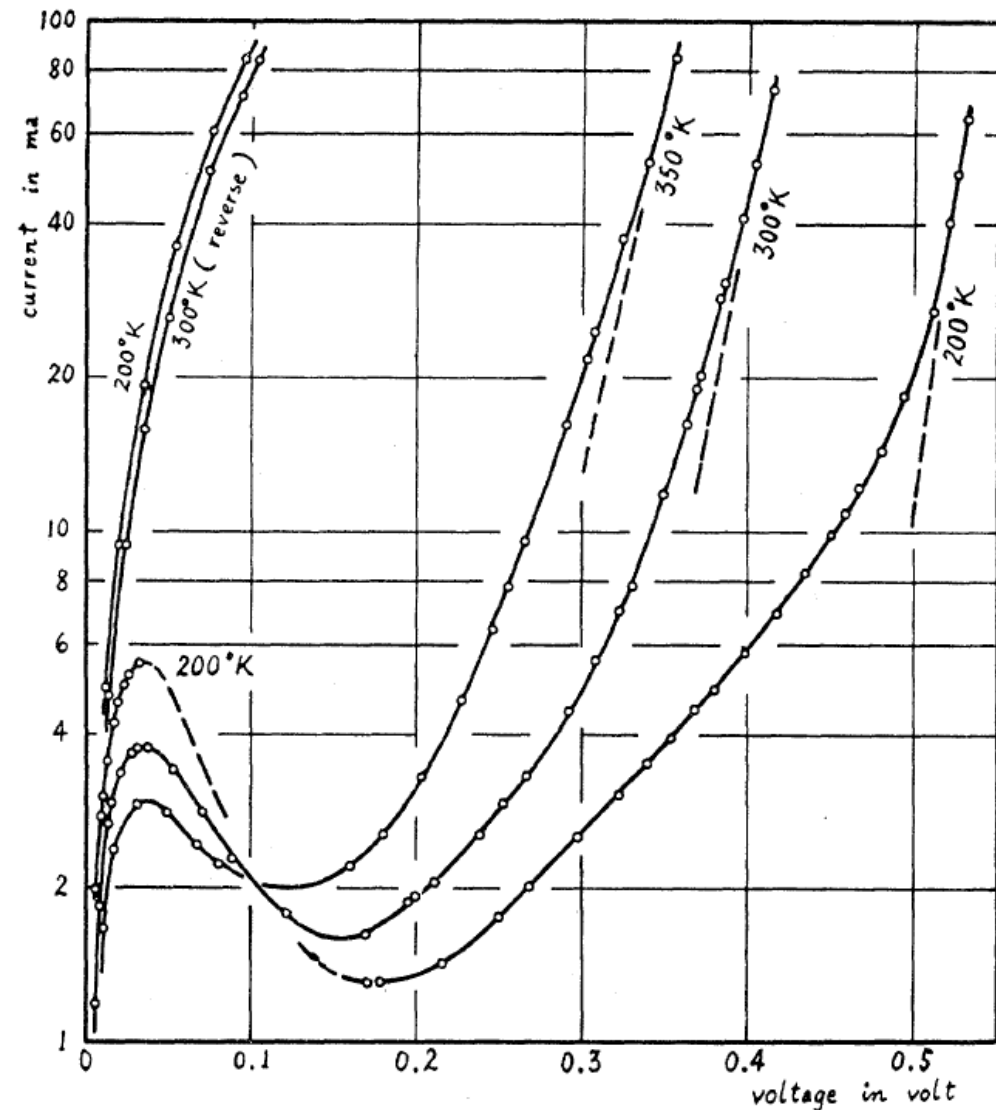


FIG. 1. Semilog plots of the measured current-voltage characteristic at 200°K, 300°K, and 350°K.

- Note the shape of the N-shaped IV characteristics
- The device active region in this case is not wide, however, (10's of microns) and not made of GaAs.
- It is made in Ge, and the active region is very thin (10's of nanometers)
- The underlying Physics is therefore very different – junction tunnelling current, rather than domain formation and propagation. High mobility is not critical here.

Esaki Diode - Rough Energy Diagram

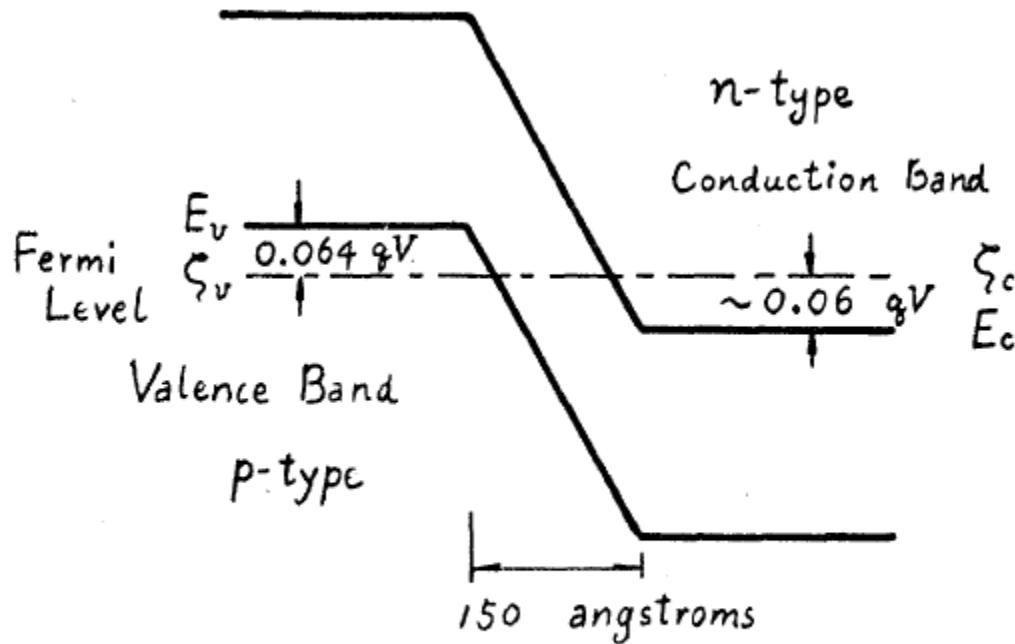


FIG. 2. Energy diagram of the p - n junction at $300^\circ K$ and no bias voltage.

- With no external bias – flat electrochemical potential is imposed.
- Because of the high doping levels on either side of the junction, the Fermi level is positioned well within the corresponding bands.
- The barrier height is approximately equal to the band gap – $0.6 eV$.
- The barrier width, inferred by capacitance, is only 15 nm , or so.

- The current conversion process must become inefficient at high bias, as there are no states available of the same type, while at the same time there is not enough energy for e - h pair generation.

Esaki Diode - Current Components

$$I_{c \rightarrow v} = A \int_{E_c}^{E_v} f_c(E) \rho_c(E) Z_{c \rightarrow v} \{1 - f_v(E)\} \rho_v(E) dE,$$

$$I_{v \rightarrow c} = A \int_{E_c}^{E_v} f_v(E) \rho_v(E) Z_{v \rightarrow c} \{1 - f_c(E)\} \rho_c(E) dE,$$

The partial currents are given by the Fermi Golden Rule as applied to tunnelling.

$$I = I_{c \rightarrow v} - I_{v \rightarrow c} = A \int_{E_c}^{E_v} \{f_c(E) - f_v(E)\} Z \rho_c(E) \rho_v(E) dE.$$

The total current is the difference.

$$I_{\text{ex}} = \frac{V_a}{R_v} \exp\left(\frac{V_a - V_v}{V_{\text{ex}}}\right)$$

The 'excess' current is due primarily to impurity and defect states tunnelling.

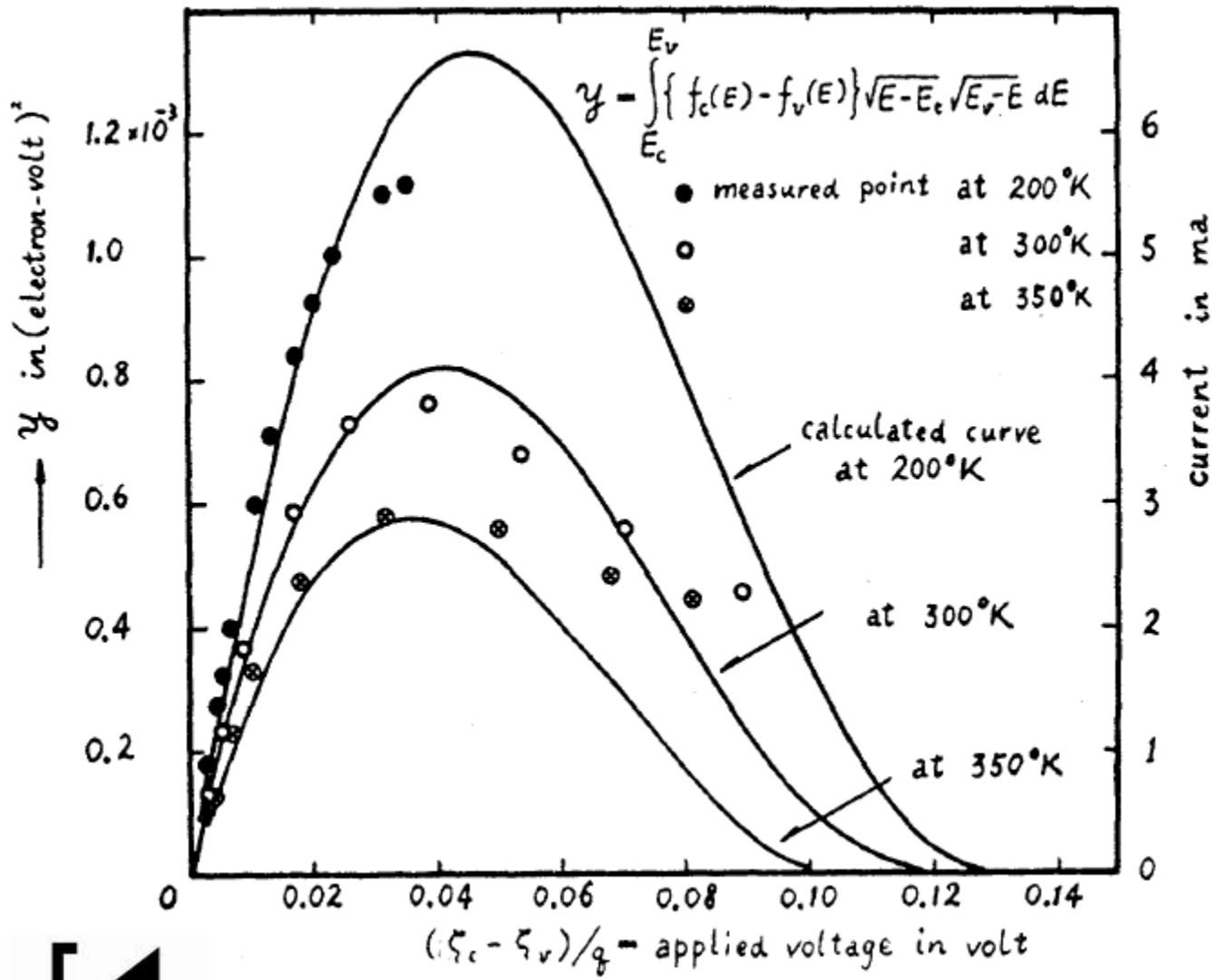
$$I_d = I_s \left(e^{V_a / \eta V_t} - 1 \right)$$

There is still a 'normal' diode component.

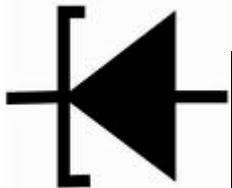
$$I_{\text{tot}} = I_t + I_{\text{ex}} + I_d$$

The total current is just a sum on all components.

Is this a Believable Explanation

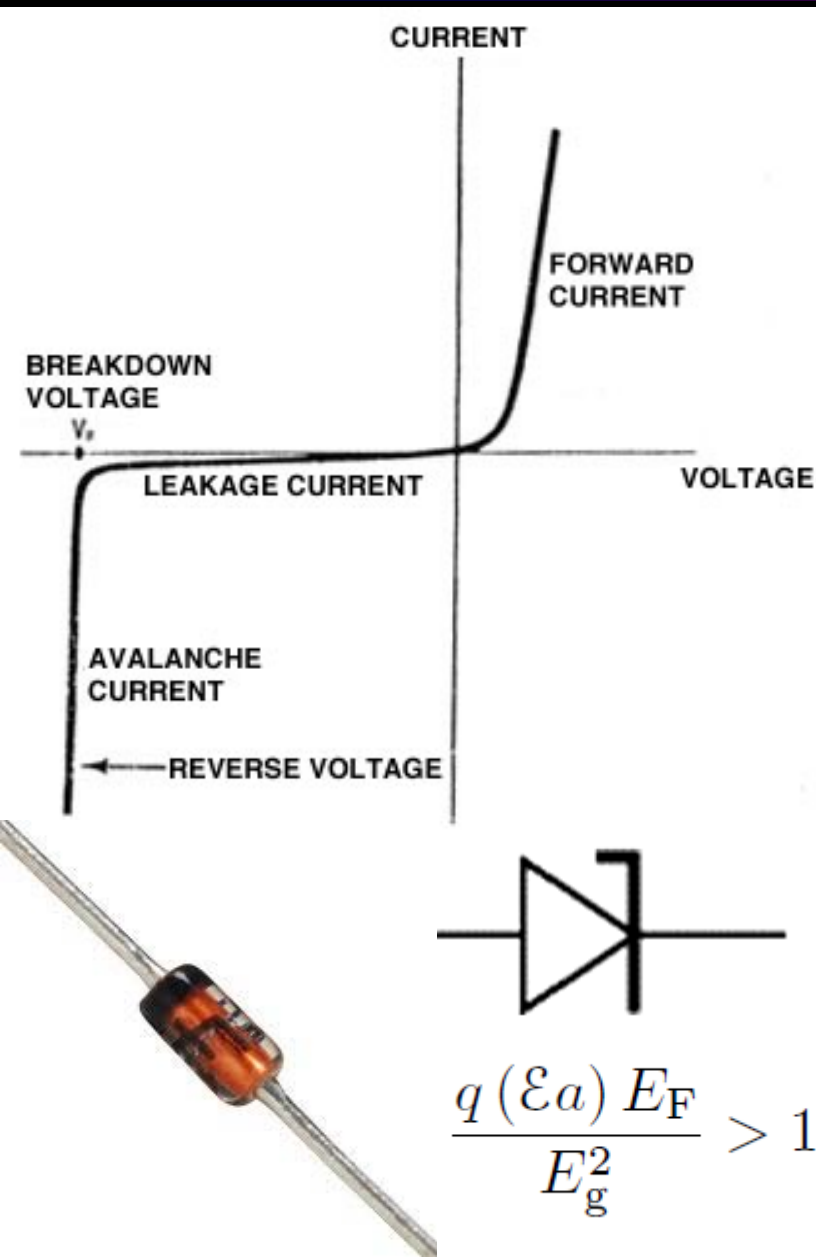


- At small bias - the agreement is good.
- The additional components are, however, necessary in order to explain the observed IV characteristics.
- The temperature dependence is rather weak (as expected) - at low bias.



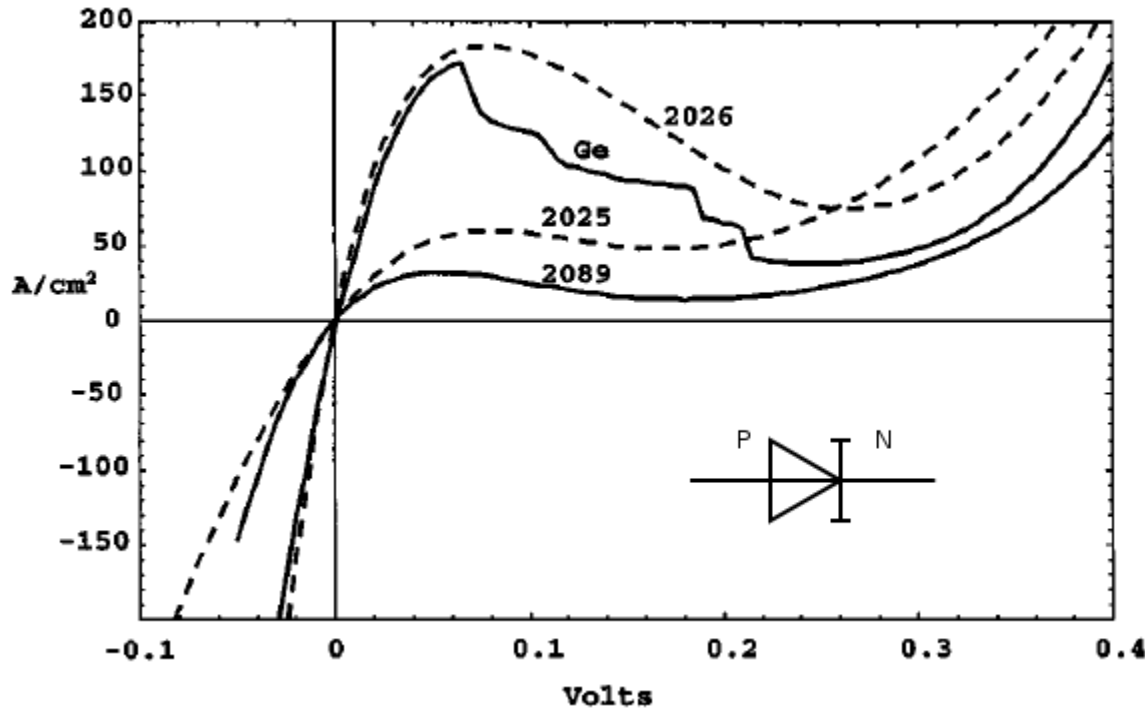
Tunnel Diode and Symbol

The Zener Diode

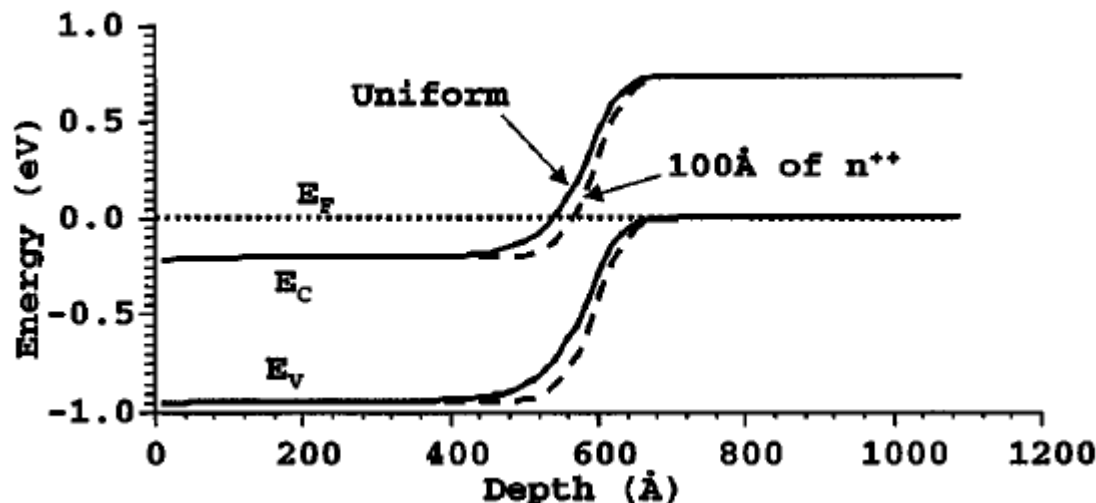


- At small reverse bias the current remains close to I_s .
- As negative bias grows, eventually the electric field within the depleted region will be sufficiently strong for thermally generated carriers to be accelerated and cause impact ionisation – *avalanche breakdown*.
- Alternatively, for a highly doped semiconductor, the depletion region is narrow and tunnelling dominates – Zener breakdown.
- Note the strong dependence on the band gap! ‘Band gap reference...’
- Small and –ve temperature coefficient

The Backward Diode



- The notions of Esaki and Zener diodes can be agglomerated together in what's called a 'backward diode'.
- This heavy-doping structure conducts better in 'reverse bias'.
- Good microwave detector – low bias, no carrier storage effects and low $1/f$ -noise (low recombination and low shot noise).



More Exotic Diodes – The λ

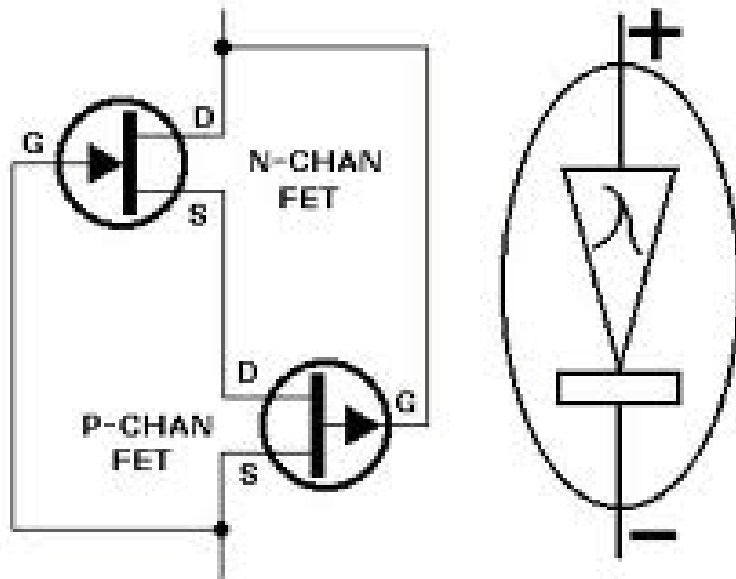
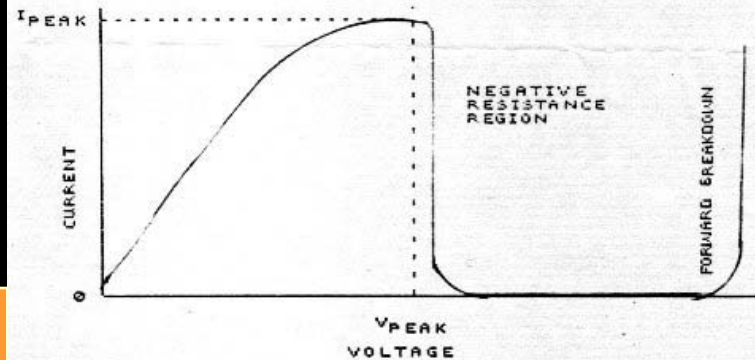
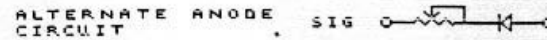
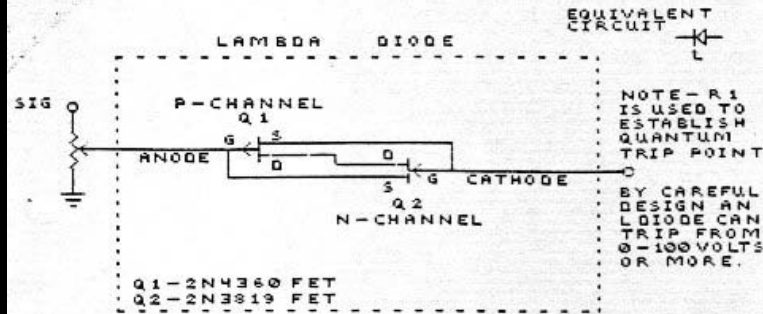


Fig 2



LAMBDA DIODE CHARACTERISTIC CURVE

LAMBDA DIODE NOTES

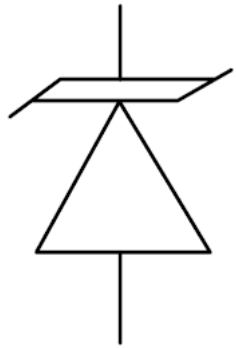
As can be seen the Lambda diode is a superior quantum device. Compare its characteristic curve with that of the tunnel diode or "Negistor" (see elsewhere). Contrary to pedestrian understanding super-conductivity is an aspect of charge (Cooper pairing of electrons) NOT the conductor. Thus the tunnel diode, Negistor and Lambda diode are room temperature super-conductors (zero ohms IS super-conductivity!).

The Lambda diode will act like a varactor diode due to its insulated gate structure. With the incorporation of two carefully matched components the Lambda diode becomes a Lambda Capacitor with capacity up to and beyond one farad (see Radio-Electronics, Mar. '85; p. 98-99 for details on a primitive capacitive multiplier). A non-polarized Lambda capacitor can be made by placing two devices in parallel.

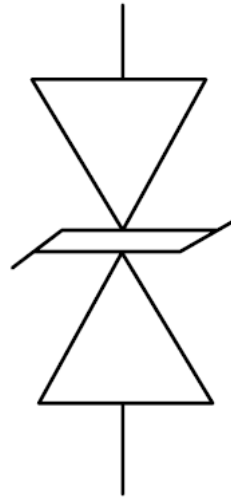


- Compound device – propagation delays would prohibit very high frequency operation
- Relies on Zener breakdown in one or more gate-source circuits
- Can have very low 'shut' current

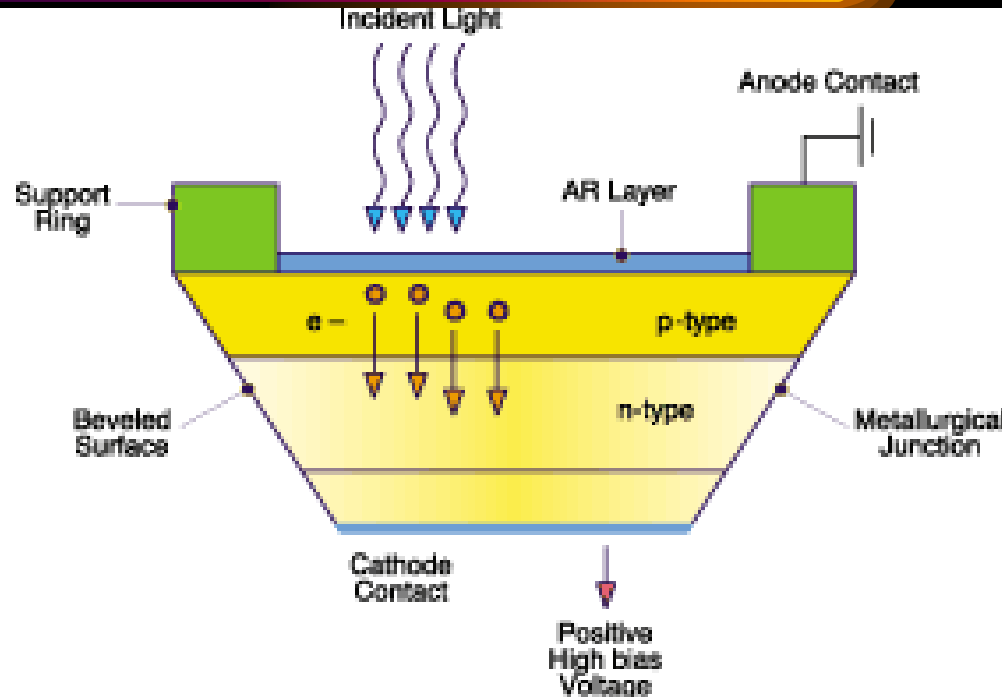
More Exotics – Avalanche detectors



Unidirectional



Bidirectional

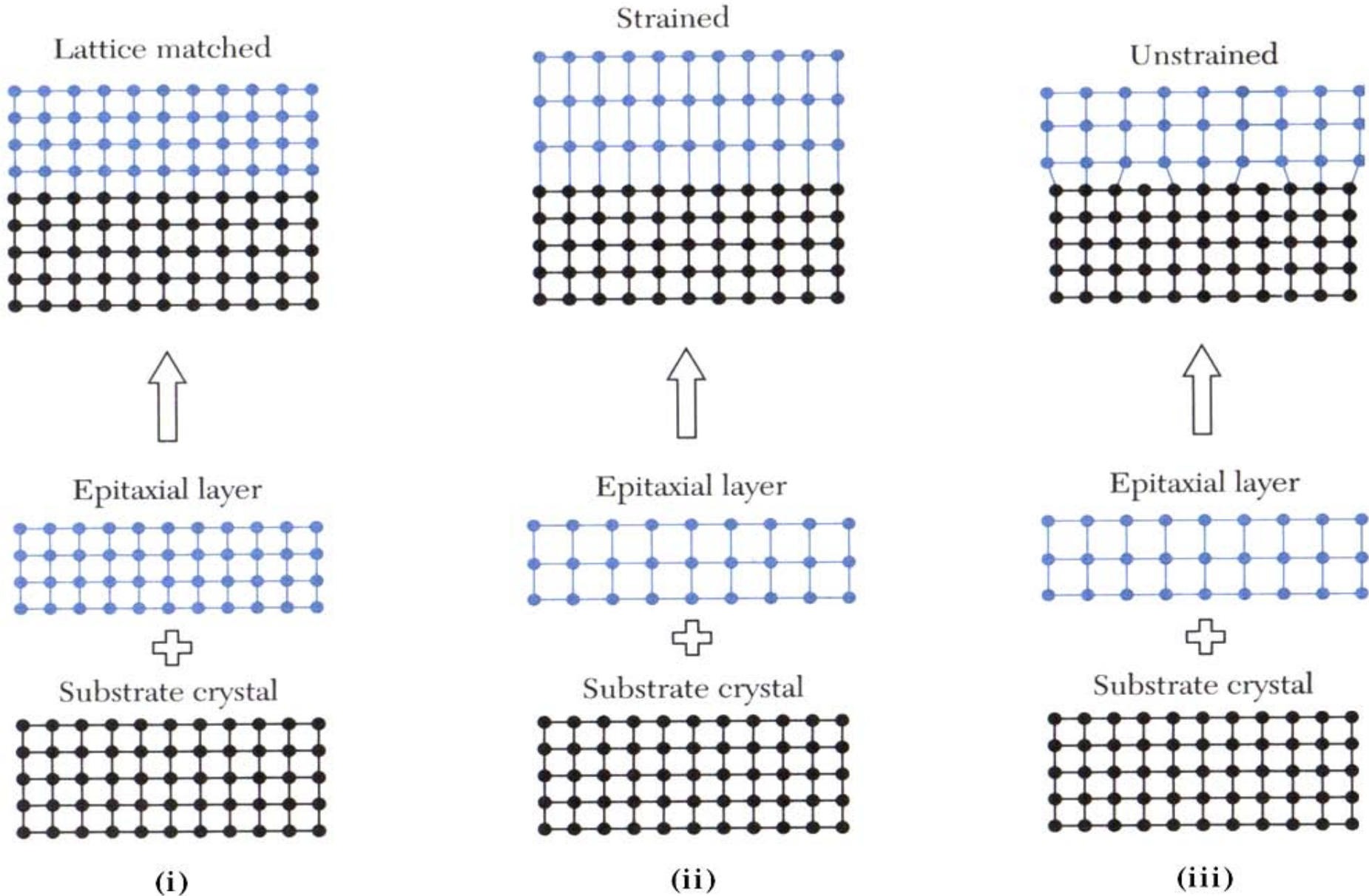


- Primarily used as photon detectors (also for alphas and soft x-rays)
- Can be also built into transistor structures with internal gain.
- Design and manufacturing quality limit the longevity
- Often cooled to lower noise (due to thermal avalanching)
- Sometimes used as noise generators (with promoted thermal averaging)
- Make the distinction from Zener diodes
- Uses in circuit protection (surge protection, or overvoltage protection)

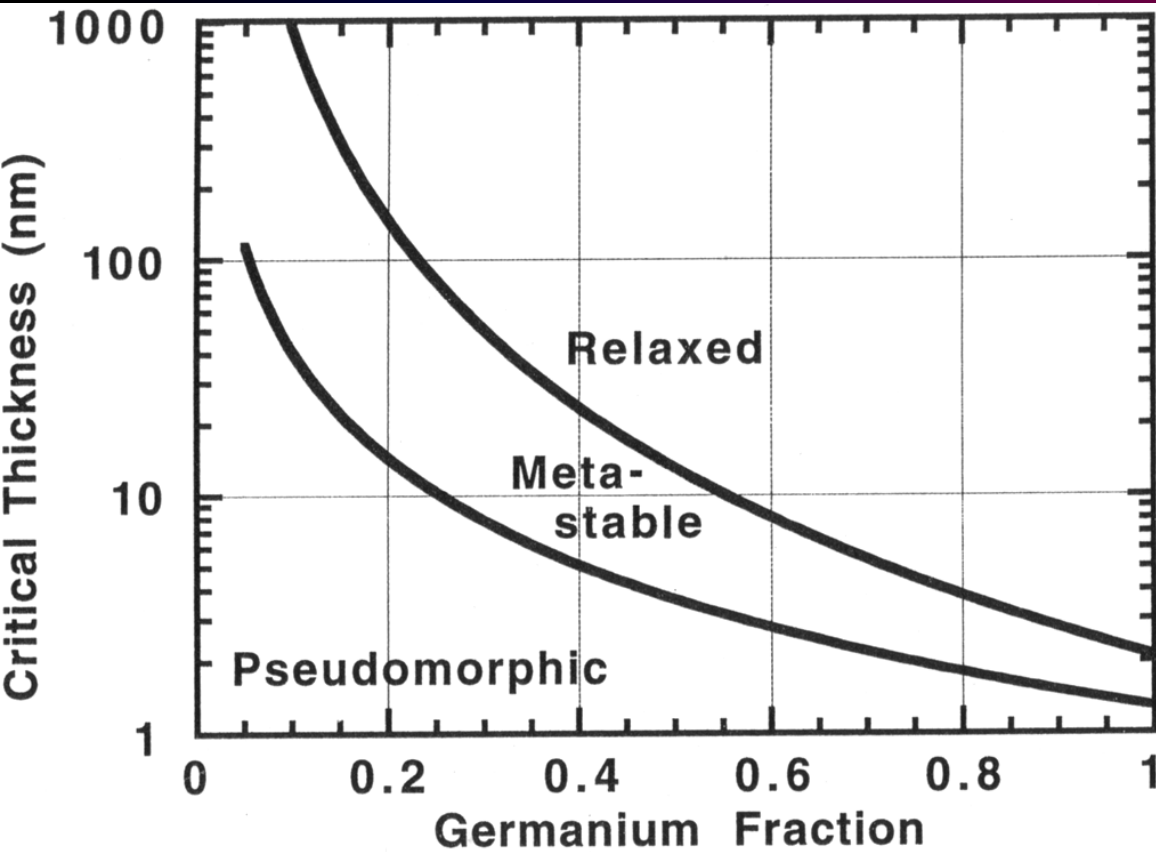
Heteroepitaxy and Heterostructures

- There are now many types of both unipolar and bipolar devices with two or more different compound semiconductors in the same device.
- There are methods for obtaining very high frequency responses with these structures. These will be discussed later.
- These devices are usually made by heteroepitaxial techniques, in which the epilayer-substrate crystal lattices must be matched up, as in homoepitaxy.
- For lattice-matched epitaxy, e.g. $\text{Al}_x\text{Ga}_{1-x}\text{As}$ on GaAs, the lattice constants are the same to within 0.13% for any value of x between 0 and 1 – case (i) on next slide.
- But in a significantly mismatched case, and to achieve new device possibilities, the epilayer should be strained (+ve or –ve), by the substrate to 'force' a match (*strained-layer epitaxy*, with *pseudomorphic* layers) – case (ii) – whereas misfit dislocations, relieving the strain, degrade device performance – case (iii).

Basic Epitaxial Relations



Methods for Strain Relief – SiGe



- Strained epilayers have a maximum critical thickness above which so many atoms are being stressed that the layer will relax by nucleating misfit dislocations in an avalanche type of process.
- E.g. consider the alloy SiGe (both group IV) – an attractive compound semiconductor, as it can be processed with conventional silicon device technology.

- The graph shows the critical thickness for strain relaxation vs germanium fraction x in $\text{Si}_{1-x}\text{Ge}_x$ grown on silicon.
- Note that dislocation mobility depends on temperature – i.e. meta-stable region.

Thanks and Acknowledgements



Thank You Very Much for Your Attention!