Lecture (10)

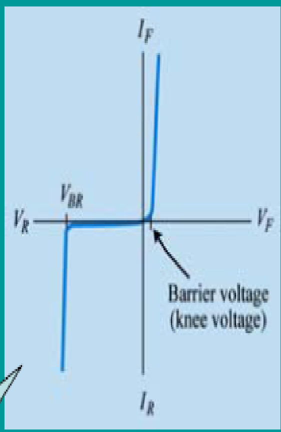
Diode Resistance

Practical Diodes

- A practical diode does offer some resistance to current flow when forward biased.
- Since there is some resistance, there will be some power dissipated when current flows through a forward biased diode. Therefore, there is a practical limit to the amount of current a diode can conduct without damage.
- A reverse biased diode has very high resistance.
- Excessive reverse bias can cause the diode to conduct.

Current versus Voltage

- In a practical diode, there is very little forward current until the barrier voltage is reached.
- When reverse biased, only a small amount of current flows as long as the reverse voltage is less than the *breakdown* voltage of the device.



Current Vs Voltage Curve for a practical diode

12

Diode Resistance

The static resistance, R_s ,of the diode is just the DC resistance we would calculate from measurement of the current through and voltage across it. This will vary depending on where we are on the I-V characteristic.

$$R_s = \frac{V}{I}$$

The dynamic resistance, r_d , of the diode is its small signal AC resistance and also depends on the point on the characteristic where it is measured. An expression for r_d can be found by differentiating the approximate diode equation for V >> 26mV with respect to V.

$$r_d = \frac{dV}{dI} = \left(\frac{dI}{dV}\right)^{-1} = \frac{\eta kT}{eI}$$

$$= \frac{26}{I(mA)}$$

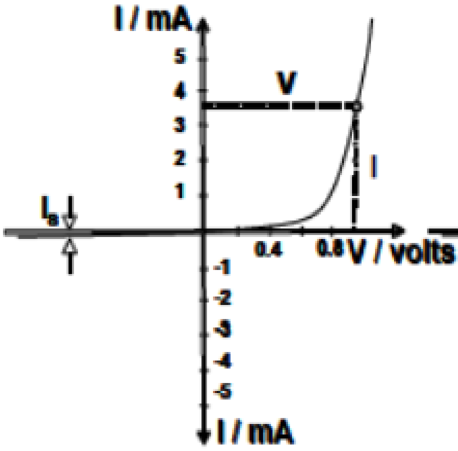
for V >> 26mV, I in mA
T = 300K and assuming η=1.

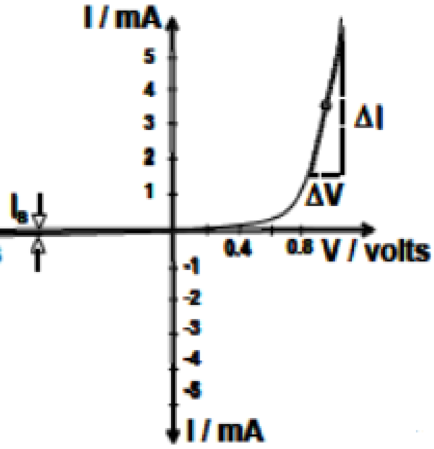
Note that the diode quantities V_o, I_s and r_d all depend on temperature.

❑ STATIC & DYNAMIC RESISTANCE

$$\boxed{R_s = \frac{V}{I}}$$

$$\boxed{r_d = \frac{dV}{dI} = \frac{\eta kT}{eI} = \frac{26}{I\ (\text{in mA})} \quad \text{for } T = 300\text{K}, \eta = 1}$$





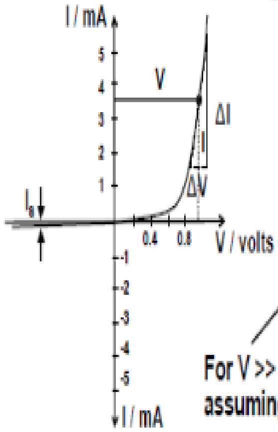
Diode resistance

$$I = I_s[\exp(\frac{eV}{\eta kT}) - 1]$$

Static resistance: $\boxed{R_s = \frac{V}{I}}$

Dynamic resistance:

$$\boxed{r_d = \frac{dV}{dI} = \left(\frac{dI}{dV}\right)^{-1} = \frac{\eta kT}{eI} = \frac{26}{I(mA)}}$$



For V >> 26 mV, I in mA and assuming T = 300 K and $\eta = 1$

Diode Capacitance

As well as having a resistance associated with it, the diode also has a capacitance. The two layers of space charge which form the depletion region on either side of the junction are analogous to the plates of a parallel-plate capacitor (see Fig. 65(a)). For such a capacitor:

$$C = \frac{\varepsilon A}{d}$$

where A is the plate area, ε is the permittivity of the medium between the plates and d is the plate separation. Hence the capacitance, C_J, of the pn junction will depend on the width, W, of the depletion region:

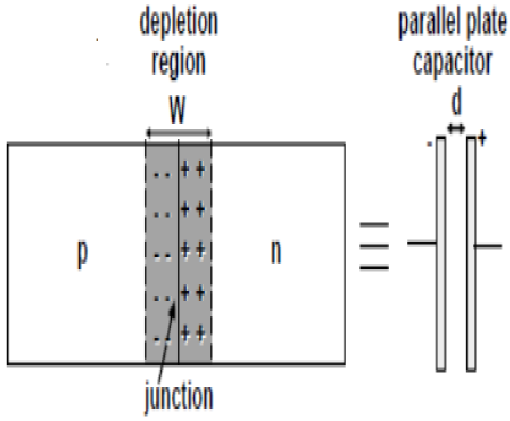
$$C_J \propto \frac{1}{W}$$

As we have already seen, W depends on the applied voltage, becoming smaller as V becomes more positive (i.e. as the forward bias is increased) and larger as V becomes more negative (i.e. as the reverse bias is increased). Taking account of this dependence, it can be shown that:

$$C_J = \frac{K}{(V_B - V)^n}$$

V_B is the barrier potential
V is the applied bias (V +ve or -ve for forward or reverse bias respectively)
K is a constant; n= ½ for abrupt junction 32

Diode Capacitance



A = plate area; ε = permittivity of medium between the plates $\quad C = \frac{\varepsilon A}{d}$

C_J is the "junction capacitance" → $C_J \propto \frac{1}{W}$

K = a constant; V_B = barrier potential
V = applied bias (-ve for reverse bias)
n = ½ for an abrupt junction $\quad C_J = \frac{K}{(V_B - V)^n}$

Diode Small Signal Model

- The I-V relation of a diode can be linearized

$$I_D + i_D = I_S\left(e^{\frac{q(V_d+v_d)}{kT}} - 1\right) \approx I_S e^{\frac{qV_d}{kT}} e^{\frac{qv_d}{kT}}$$

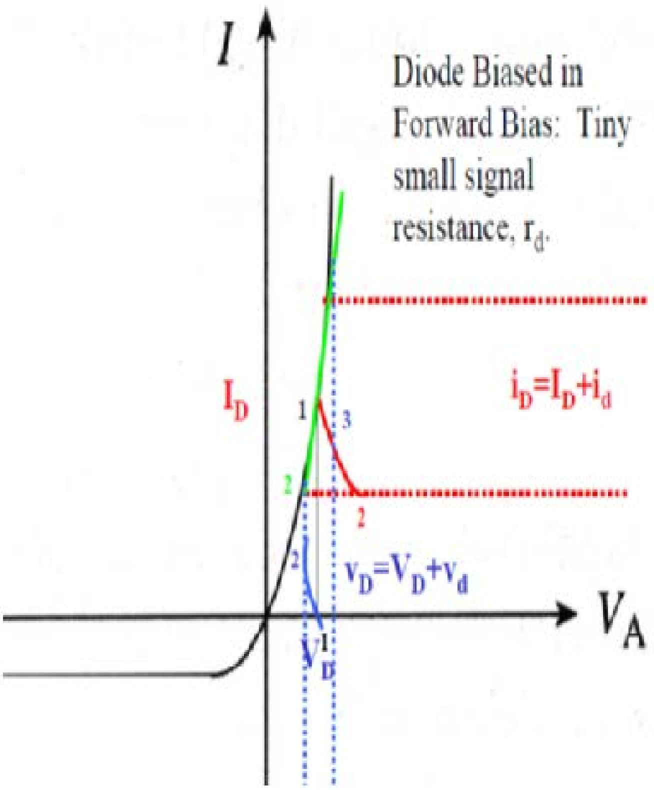
$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots$$

$$I_D + i_D \approx I_D\left(1 + \frac{qv_d}{kT} + \cdots\right)$$

$$I_D = I_S e^{\frac{qV_d}{kT}} \qquad i_D \approx \frac{qI_D}{kT} v_d = g_d v_d$$

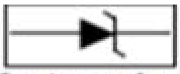
The small signal model of a diode in forward bias is a resistance in parallel with a capacitance. In reverse, it is just a capacitance. (the reverse leakage current is constant, thus no contribution to small signal)

Small Signal Analysis of Diodes



ZENER DIODE

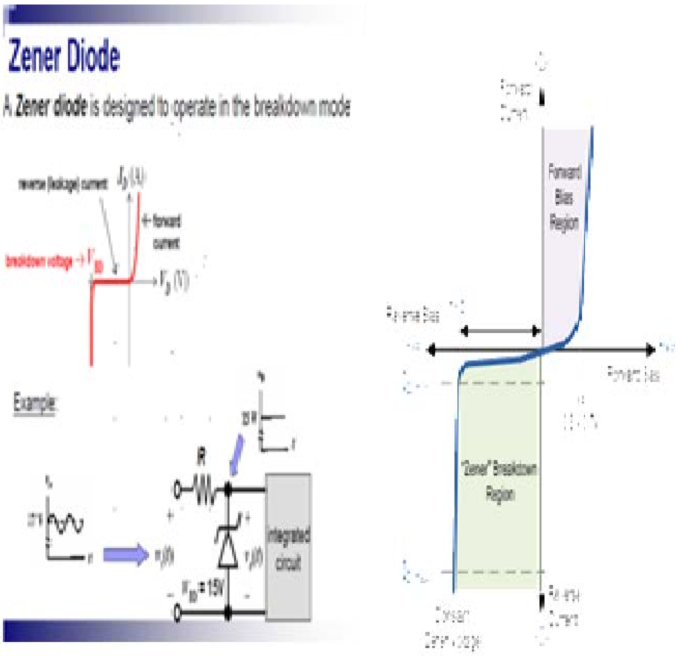
Zener Diodes:



The breakdown effect can be used as the basis of a voltage reference – diodes designed for this application are termed "Zener Diodes"

Zener diodes

- Diodes which are called Zener diodes do not use the Zener effect (tunneling) but are avalanche breakdown devices.
- With the application of sufficient reverse voltage, a p-n junction will experience a rapid avalanche breakdown and conduct current in the reverse direction.
- Under a high electric field, high energy carriers can cause the generation of more electron hole pairs, and the subsequent collisions quickly become an avalanche. When this process is taking place, very small changes in voltage can cause very large changes in current.
- Zener diodes can be made which break down at precise voltages from about 4 volts to several hundred volts. The avalanche breakdown occurs at a particular field strength, so the high field region just needs to be the correct length
- Avalanche breakdown does not damage the diode as long as power dissipation limits are not exceeded.



The p-n junction diode that operates in the reverse breakdown region is usually destroyed by the excess current and the heat it produces. The **zener** diode is designed to successfully operate in this region.
The characteristic curve of the zener operating in the reverse breakdown region shows that the voltage dropped across the zener diode remains relatively constant while current through the zener current is allowed to increase dramatically When forward biased, the zener has a turn-on voltage of approximately 0.7 V (like any other silicon diode.) When reverse biased, the zener can have a “zener voltage” equal to whatever amplitude it is designed (and doped) to possess (from a minimum of approximately 1.8 V to several hundred volts.)
The relatively constant voltage drop across the zener when it is reverse biased is the reason for to its use as a **voltage regulator**. A voltage regulator is a device (or circuit) designed to maintain a constant output voltage regardless of any variations in the magnitude of its input voltage or in the requirements of load current.
Characterization Zener Diode

- ✓ ☐**Normally operated in reverse-biased mode**
- ✓ ☐**The reverse voltage across the diode is almost constant**
- ✓ ☐**The reverse current flowing across the diode may vary within a specified range**.
- ✓ ☐**Acts as normal diode when forward biased**

VARACTOR DIODE

What is a Tuning / Varactor Diode?

Varactor diodes, also known as varicap diodes, are a simple electronic component. A type of simple semiconductor diode commonly used in electronics such as parametric amplifiers, filters, oscillators and frequency synthesizers, varactor diodes have a variable capacitance, which is a function of the voltage impressed on its terminals. In electronics, varactor diodes are mostly utilized as voltage-controlled capacitors.

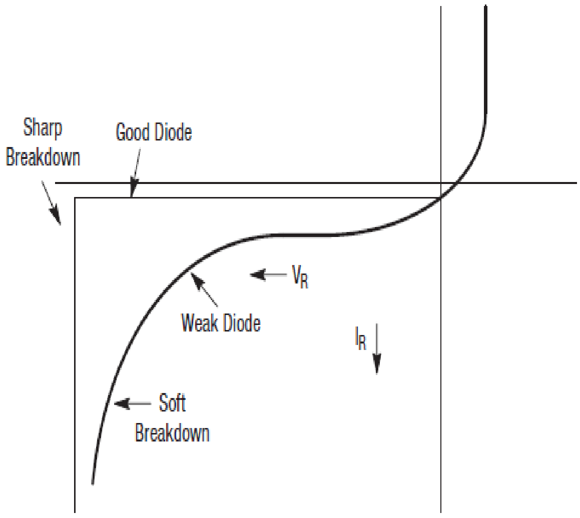
Operation

Tuning / varactor diodes are operated reverse-biased, and therefore no current flows. However, since the thickness of the depletion zone varies with the applied bias voltage, the capacitance of the diode can be made to vary. Usually, the capacitance is inversely proportional to the depletion region thickness and the depletion region thickness is proportional to the square root of the applied voltage. Therefore, the capacitance is inversely proportional to the square root of the voltage applied to the diode.

Varactor diodes are constructed in the same way as a capacitor and operate under reverse bias conditions, which gives rise to three current-conducting regions. Currents conduct through positive (P) and negative (N) regions, located at either end of the diode. Near the junction of the P and N regions, a depletion region ensures that no current carriers are available, thus acting as an insulator. Due to this arrangement, a varactor diode’s conductive plates are separated by an insulator like dielectric, much like a capacitor.

Reverse Breakdown

Varactor diodes are designed to provide voltage-controlled capacitance via operation under reverse bias. A diode's reverse breakdown is defined by the minimum reverse voltage required to make the diode conduct in reverse. As reverse bias increases, capacitance decreases; the maximum voltage that a varactor diode can withstand is determined by its maximum capacitance level. The reverse bias of most varactor diodes operates from around a few volts up to about 20 volts, with some rare exceptions operating up to 60 volts. As a varactor diode's voltage increases, specific energy supplies must be provided for the circuits driving the diode. The IV characteristics of a good-quality diode and a weak diode are depicted in the following figure.



Applications for Tuning / Varactor Diodes:

Tuning / varactor diodes are often used in RF design. They are often used in pairs to switch between two different R.F. sources such as the V.H.F. and U.H.F. bands in a television tuner by supplying them with complimentary bias voltages.

They can also be found in RF filters for tuning purposes (for example, as tuners of television sets to electronically tune the receiver to different stations), parametric amplifiers, parametric oscillators and frequency synthesizers.

Key Electrical Parameters

The key electrical parameters guiding the selection and usage of a varactor diode are

_ Reverse breakdown voltage and reverse leakage current.

_ Capacitance value and the capacitance-voltage change behavior.

_ Quality factor (also known as figure of merit),

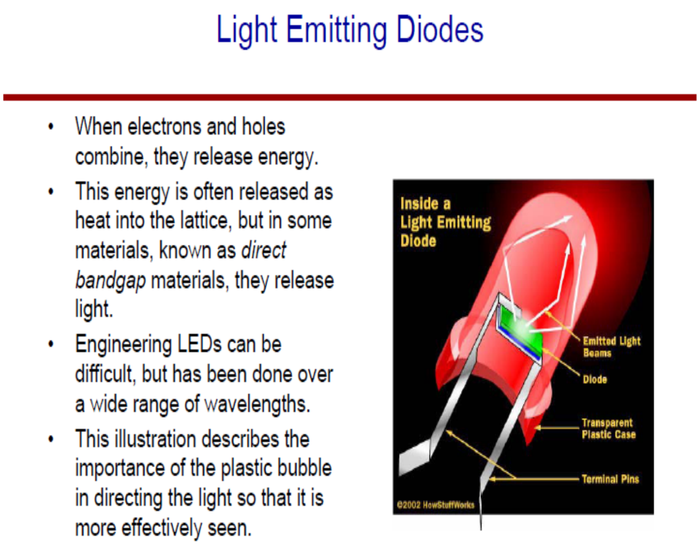
Light-emitting diodes (LEDs)

The light output of an LED is the spontaneous emission generated by radiative recombination of electrons and holes in the active region of the diode under forward bias.

• The semiconductor material is direct-bandgap to ensure high **quantum efficiency**, often III-V semiconductors.

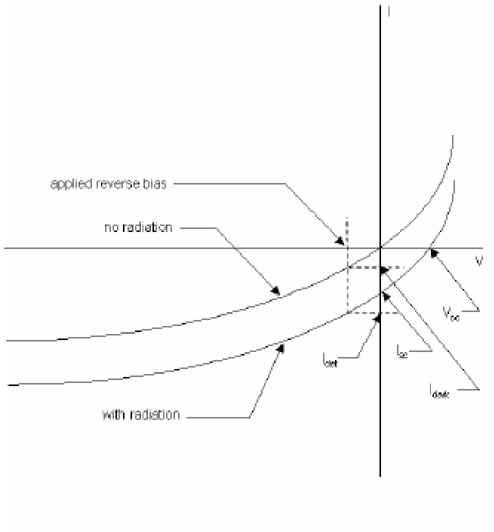
• An LED emits incoherent, non-directional, and unpolarized spontaneous photons that are not amplified by stimulated emission.

• An LED does not have a threshold current. It starts emitting light as soon as an injection current flows across the junction



Photodiodes

- Diodes have an optical generation rate. Carriers are created by shining light with photon energy greater than the bandgap.
- One wants large depletion widths and long diffusion lengths, as it is only in these areas that excited carriers will make it across the junction.
- Photodetector: operate in third quadrant. Compromise between speed and junction width leads to a p-intrisic-n junction, where carriers will be rapidly swept across, and can quickly diffuse in the p and nregions.
- Solar Cell: operating in the fourth quadrant generates current, though small.

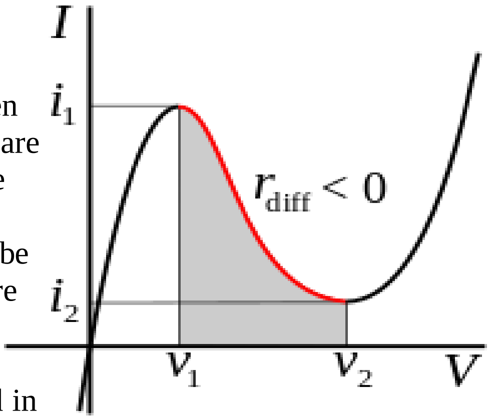


Tunnel Diodes (Esaki Diode)

A **tunnel diode** or **Esaki diode** is a type of semiconductor that is capable of very fast operation, well into the microwave frequency region, made possible by the use of the quantum mechanical effect called tunneling.

These diodes have a heavily doped p–n junction only some

10 nm (100 Å) wide. The heavy doping results in a broken bandgap, where conduction band electron states on the n-side are more or less aligned with valence band hole states on the p-side



Tunnel diodes are usually made from germanium, but can also be made from gallium arsenide and silicon materials. They are used in frequency converters and detectors.[4] They have negative differential resistance in part of their operating range, and therefore are also used as oscillators, amplifiers, and in switching circuits using hysteresis.

Forward bias operation

Under normal forward bias operation, as voltage begins to increase, electrons at first tunnel through the very narrow p–n junction barrier because filled electron states in the conduction band on the n-side become aligned with empty valence band hole states on the p-side of the p-n junction. As voltage increases further these states become more misaligned and the current drops – this is called *negative resistance* because current decreases with increasing voltage. As voltage increases yet further, the diode begins to operate as a normal diode, where electrons travel by conduction across the p–n junction, and no longer by tunneling through the p–n junction barrier. The most important operating region for a tunnel diode is the negative resistance region.

Reverse bias operation

When used in the reverse direction, tunnel diodes are called **back diodes** (or **backward diodes**) and can act as fast rectifiers with zero offset voltage and extreme linearity for power signals (they have an accurate square law characteristic in the reverse direction). Under reverse bias, filled states on the p-side become increasingly aligned with empty states on the n-side and electrons now tunnel through the pn junction barrier in reverse direction.

Applications for tunnel diodes included local oscillators for UHF television tuners, trigger circuits in oscilloscopes, high-speed counter circuits, and very fast-rise time pulse generator circuits. The tunnel diode can also be used as low-noise microwave amplifier. Tunnel diodes are also more resistant to nuclear radiation than other diodes. This makes them well suited to higher radiation environments such as those found in space.

LASER DIODE

What is LASER? Light Amplification by Stimulated Emission of Radiation
•Many types of laser:
•solid-state laser, gas laser, dye laser, semiconductor laser…

laser diode is an electrically pumped semiconductor laser in which the active medium is formed by a p-n junction of a semiconductor diode similar to that found in a light-emitting diode. The laser diode is distinct from the optically pumped semiconductor laser, in which, while also semiconductor based, the medium is pumped by a light beam rather than electric current
• A laser diode (LD) is a semiconductor optical amplifier (SOA) that has an optical feedback.
• A semiconductor optical amplifier is a *forward*-biased *heavily-doped* p+-n+ junction fabricated from a *direct*-band gap semiconductor material.
• The injected current is sufficiently large to provide *optical gain*.
• The optical feedback is usually implemented by *cleaving* the semiconductor material along its crystal planes.
• The sharp refractive index difference between the crystal (~3.5) and the surrounding air causes the cleaved surfaces to act as reflectors.

Properties:

1- laser light wavelength = 800-840 nm
2- output power (CW) = 5-10 Mw & in (pulsed) = 15 W
3- Bandwidth = 10^{11} Hz (A relatively *narrow spectral width* of the emitted light allows operation at high bit rates (~ 10 Gb/s), as *fiber dispersion* becomes less critical for such an optical source.)
4- Efficiency = 10%
5- S.C laser cover =(0.7-30 µ

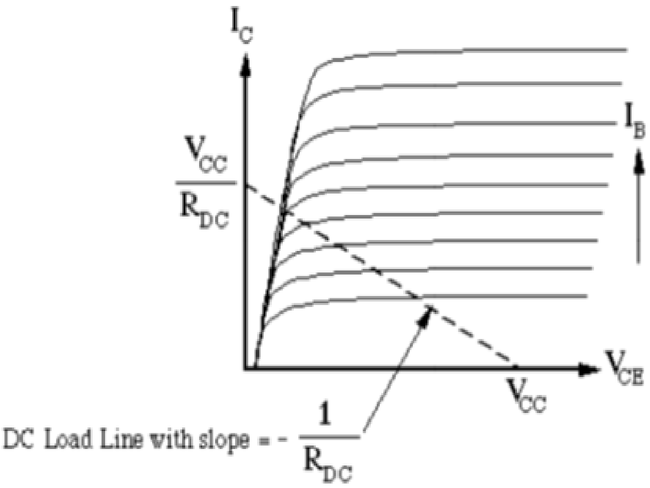
Applications

• Telecommunications
– modulation, tunability
• Sensing

– Wavelength, tunability
• Coder reading
• I-R source
• Processing
– Power, wavelength, efficiency.

The Load lines concept

A **load line** is used in graphical analysis of nonlinear electronic circuits, repre senting the constraint other parts of the circuit place on a non-linear device, like a diode or transistor. It is usually drawn on a graph of the current vs the voltage in the nonlinear device, called the device's characteristic curve. A load line, usually a straight line, represents the response of the linear part of the circuit, connected to the nonlinear device in question. The operating point(s) of the circuit are the points where the characteristic curve and the load line intersect; at these points the current and voltage parameters of both parts of the circuit match.



The example at right shows how a load line is used to determine the current and voltage in a simple diode circuit. The diode, a nonlinear device, is in series with a linear circuit consisting of a resistor, R and a voltage source, V_{DD}. The characteristic curve *(curved line)*, representing current *I* through the diode versus voltage across the diode V_D, is an exponential curve. The load line *(diagonal line)* represents the relationship between current and voltage due to Kirchhoff's voltage law applied to the resistor and voltage source, is

$$V_D = V_{DD} - IR$$

Since the current going through the three elements in series must be the same, and the voltage at the terminals of the diode must be the same, the operating point of the circuit will be at the intersection of the curve with the load line.