Lecture 11 - Microwave Semiconductors and Diodes

Microwave Active Circuit Analysis and Design

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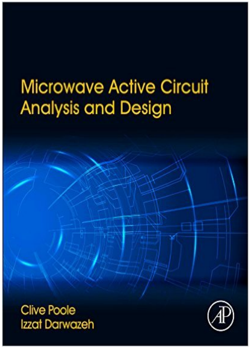

Intended Learning Outcomes

- Knowledge
  - Be aware of the various types of compound semiconductors that are used at microwave frequencies.
  - Be acquainted with the basic fabrication processes for microwave semiconductor devices, such as photolithography and Molecular Beam Epitaxy (MBE).
  - Be familiar with the various types of microwave diode, such as Tunnel, IMPATT, TRAPATT and Gunn diodes, their equivalent circuits and applications.
  - Understand the concept of *dynamic negative resistance* as it applies to microwave two terminal device.
  - Understand the operating principle and application of the varactor diode and the effect of doping profile on electrical characteristics.
- Skills
  - Be able to work out the doping profile of a varactor needed to achieve a particular C-V characteristic.
  - Be able to design basic microwave negative resistance diode circuits using the load line concept.
  - Be able to determine the oscillation frequency of a Gunn diode of specific geometry and design a simple Gunn diode oscillator.
  - Be able to design a PIN diode attenuator.

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Semiconductor physics recap

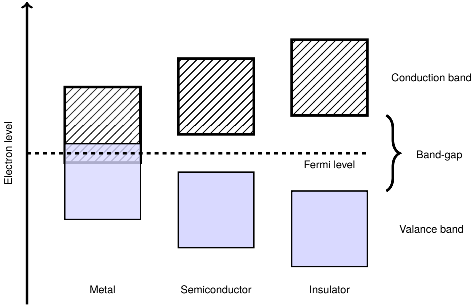

Figure 1 : Electronic band structures of metals, semiconductors and insulators

Table 1 : Groups 2 to 6 of the periodic table

II	III	IV	V	VI
	Bo	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te
Hg	Tl	Pb	Bi	Po

Semiconductor physics recap

Table 2 shows part of groups 2 (II) to 6 (VI) of the periodic table which is the region containing the semiconducting elements. The most well known of these are Silicon (Si) and Germanium (Ge). Certain elements in Groups III and V, or Groups II and VI, or groups IV and VI of the periodic table may be combined to form what are called *Compound Semiconductors*.

Table 2 : Groups 2 to 6 of the periodic table

II	III	IV	V	VI
	Bo	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te
Hg	Tl	Pb	Bi	Po

Semiconductor materials : Silicon and Silicon-Germanium

- The widespread use of silicon across the electronics industry results in the ready availability of silicon fabs, used for huge production volumes. This results in relatively low cost of silicon device fabrication as compared with other semiconductor materials.
- SiGe is not fabricated as a bulk semiconductor material, but as the base region of a transistor in an otherwise silicon wafer. The addition of germanium allows higher dopant concentrations in the base region of the transistor because a band-gap now exists between the base and the emitter.
- Higher doping concentration in the base region means that the base can be made narrower which speeds up the transit time.
- The development of Silicon-Germanium technology is intimately linked to the development of the Heterojunction Bipolar Transistor (HBT). The first SiGe heterojunction Bipolar Transistor was reported by IBM in 1987 [3] and since then SiGe devices have become commonplace in microwave active devices up to the low tens or even hundreds of GHz.

Semiconductor materials : Gallium Arsenide (GaAs)

- Gallium Arsenide was the first compound semiconductor to extend the frequency of operation of active devices beyond what was possible with silicon. GaAs was also the material within which the *transferred electron effect* was first discovered [2, 5], which enabled the production of negative resistance Gunn diodes.
- The first GaAs diode was reported in 1958[4] and GaAs transistors started to appear in the 1960s[8].
- Key advantages of GaAs over silicon are [22, 19]:
  - GaAs has higher saturated electron drift velocity and low field mobility than Silicon. This leads to faster devices.
  - GaAs can be made with high resistivity which makes it an excellent substrate for microwave low loss passive components.
  - Silicon has higher substrate loss at microwave frequencies. GaAs has a much higher resistivity than silicon (ref. table **??**), to the extent that it is often referred to as a 'semi-insulator'. This facilitates devices with low parasitics and good inter-device isolation.

Semiconductor materials : Indium Phosphide (InP)

- Indium Phosphide (InP) has superior electron velocity with respect to both Silicon and Gallium Arsenide.
- InP has had an established presence for some time as a common material for optoelectronics devices like laser diodes. It is also used as a substrate for epitaxial Indium Gallium Arsenide based optoelectronic devices.
- In terms of high frequency active device properties, InP surpasses both Silicon and GaAs with submillimeter wave MMICs being now routinely fabricated in InP [12, 11].

Semiconductor materials : Silicon Carbide (SiC)

- Silicon Carbide (SiC) is a wide band-gap semiconductor material, making it applicable for short wavelength optoelectronic, high temperature, radiation resistant, and high-power/high-frequency applications.
- Electronic devices made from SiC can operate at extremely high temperatures without suffering from intrinsic conduction effects because of the wide energy band-gap.
- SiC can withstand a voltage gradient (or electric field) over eight times greater than Si or GaAs without undergoing avalanche breakdown. This high breakdown electric field enables the fabrication of very high-voltage, high-power devices. Additionally, it allows the devices to be placed very close together, providing high device packing density for integrated circuits.
- At room temperature, SiC has a higher thermal conductivity than any metal. This property enables SiC devices to operate at extremely high power levels.
- SiC devices can operate at extremely high frequencies because of the high saturated electron drift velocity. SiC power MESFETs have been reported with multi-octave to decade bandwidths [14].

Semiconductor materials : Gallium Nitride (GaN)

- Gallium Nitride (GaN) is a wide band-gap semiconductor that has been commonly used in bright light-emitting diodes since the 1990s.
- More recently GaN has been used to manufacture microwave active devices and MMICs offering high power density, high voltage operation, higher reliability, and very wideband performance.
- By comparison to some other compound semiconductors, GaN has a higher resistance to ionising radiation, making it a suitable material for solar cell arrays for spacecraft and some military applications [6].
- The high temperature and high operating voltage characteristics of GaN transistors finds them increasingly used as power amplifiers at microwave frequencies [9].

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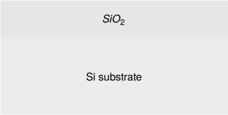
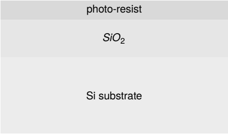
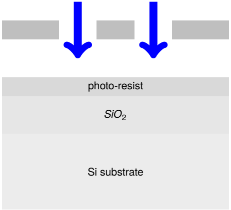
Photo-lithography



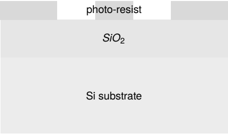
(a) Cleaning and preparation



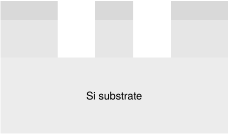
(b) photo-resist application



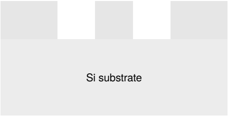
(c) photo-resist exposure



(d) photo-resist developing



(e) Etching



(f) photo-resist removal

Molecular Beam Epitaxy

- Molecular Beam Epitaxy (MBE) is a precision process that involves firing molecular beams of different semiconductor elements at a sample so as to build up thin layers of different materials.
- Typically, each element is delivered in a separately controlled beam, so the choice of elements and their relative concentrations can be adjusted for any given layer, thereby defining the precise composition and electrical and optical characteristics of that layer.

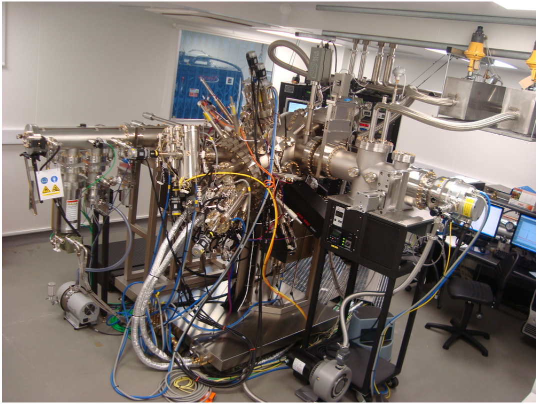


Figure 2 : MBE equipment at UCL

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The pn-junction

- When two semiconductor materials are brought into contact, the Fermi levels have to become aligned so as to be the same throughout the crystal.
- Surplus electrons from the *n*-region will diffuse into the *p*-region leaving a region of net positive charge in the *n*-region, near the junction. Similarly, surplus holes from the *p*-region will diffuse into the *n*-region leaving a region of net negative charge in the *p*-region, near the junction.
- The region immediately either side of the junction will now have been depleted of majority carriers, and is therefore referred to as the *depletion region*, also referred to as the *space charge* region, as illustrated in figure 3.

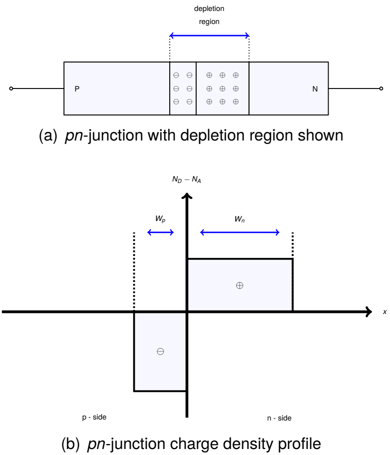

Figure 3 : Simplified representation of a *pn*-junction

The pn-junction

With no external applied voltage a potential will exist across the *pn*-junction due to the build up of carriers on each side. This is known as the *built-in* potential, and is given by [17, 15]:

$$V_o = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) \qquad (1)$$

Where N_D and N_A are the concentrations of donors and acceptors (in the n and p sides), respectively, and n_i is the concentration of electrons or holes in the intrinsic semiconductor material. As an example, n_i for some important semiconductors is listed in table 3

If we denote the width of the depletion region on the p side by W_p and on the n side by W_n, as per figure 3(b), we can state the *charge equality condition* as [17]:

$$qW_pAN_A = qW_nAN_D \qquad (2)$$

Where A is the cross-sectional area of the junction.

Table 3 : Intrinsic carrier concentrations for common semiconductors

Material	$n_i(cm^{-3})$
Germanium	2.4×10^{13}
Silicon	1.45×10^{10}
Gallium Arsenide	1.79×10^{6}
Indium Phosphide	3.3×10^{7}
Gallium Nitride	10^{10}

The pn-junction

Equation (2) can be rearranged to give :

$$\frac{W_n}{W_p} = \frac{N_A}{N_D} \tag{3}$$

In other words, the ratio or depletion region widths on the *p* and *n* sides is the inverse of the ratio of the respective doping levels. Standard semiconductor physics textbooks [17, 10] give the total width of the depletion region as:

$$W = W_n + W_p = \sqrt{\frac{2\varepsilon_r\varepsilon_o V_o}{q} \cdot \left(\frac{1}{N_A} + \frac{1}{N_D}\right)} \tag{4}$$

When a forward bias is applied externally, the depletion region shrinks as negative charge carriers are repelled from the negative terminal towards the junction and holes are repelled from the positive terminal towards the junction. This reduces the energy required for charge carriers to cross the depletion region. As the applied voltage increases, current starts to flow across the junction once the applied voltage reaches the *Barrier potential* [20].

The pn-junction

In the forward biased mode, the current through the diode, I, as a function of applied voltage, V, is defined by the *Shockley diode equation* [17]:

$$I = I_S \left(e^{\frac{qV}{kT}} - 1 \right) \qquad (5)$$

Where I_o is the reverse *Saturation Current* of the *pn*-junction. When any forward bias voltage significantly greater than V_T is applied, the exponential term in (5) becomes much greater than unity and the current increases exponentially with applied voltage, as shown in figure 5.

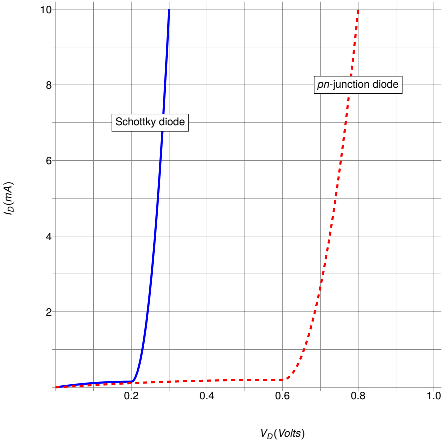

Figure 4 : Schottky diode vs *pn*-junction forward bias characteristics (Silicon)

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The Schottky Diode

- Schottky Diodes employ a Metal-Semiconductor Contact Junction. There is no *pn*-junction, as such.
- Schottky Diodes have very fast switching times due to their small capacitance and the fact that they are *majority carrier* devices.
- Schottky diodes have a very short reverse *recovery time*. For *pn*-junctions, the reverse recovery time is between 5 to 100 nS. For a Schottky diode it is normally between 5 and 100 nS.
- Schottky diodes are widely used in RF circuits as mixers and detectors.

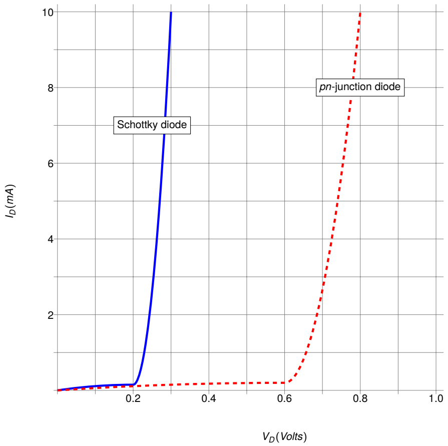


Figure 5 : Schottky diode vs *pn*-junction forward bias characteristics (Silicon)

Varactor Diode

A reverse biased *pn*-junction will exhibit a capacitance which will be a function of the reverse bias voltage.

A varactor is simply a *pn*-junction diode that has been engineered to maximise the value and range of junction capacitance with the goal of applying the device as a voltage controlled capacitor in various tuned circuits such as filters and oscillators.

Varactors are widely applied as electronic tuning devices in microwave systems.

Suppose a *pn*-junction is reversed biased (so almost no current flows). If the reverse bias is increased then the two parts of the depletion layer will widen by an amount ΔW_p and ΔW_n on the respective sides, as shown in figure 6 :

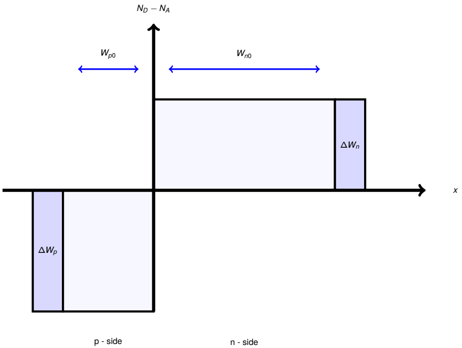


Figure 6 : Varactor depletion layer

Varactor Construction

Figure 7 is a simplified cross section of a typical discrete varactor diode fabricated using a *mesa* structure, as opposed to the planar structure used for MMIC. The mesa structure is a 'table shaped' structure, as shown in Figure 7, which avoids the high field regions at the edges, which tends to occur in planar structures. Most discrete varactors are manufactured in this format.

The varactor shown in figure 7 resembles a conventional *pn*-junction diode formed on top of a low-resistance substrate layer consisting of highly doped $N+$ material.

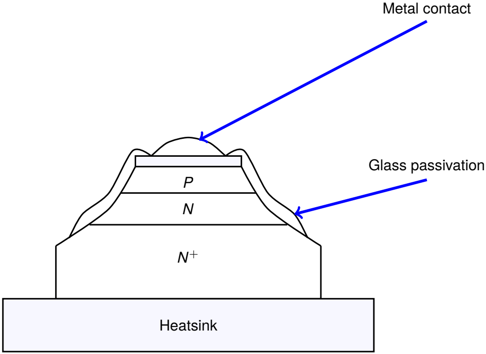


Figure 7 : Varactor diode construction

Varactor equivalent circuit

- A simplified equivalent circuit for a varactor is shown in figure 8.
- The capacitor C_j is the variable junction capacitance we are primarily interested in. The series resistance, R_S, models the resistance of the semiconductor in the areas outside the depletion region, plus the parasitic resistance of the lead and package elements.
- The resistor R_j represents the junction leakage resistance in reverse bias. Like C_j, R_j is a function of the applied reverse bias voltage.
- Depending on the type of package and the frequency range, the model may need to include some inductive elements, which we have omitted for the time being.

Typical component values in figure 8 are :

$$R_S = 0.4 \text{ to } 0.8\Omega \quad (6)$$

$$C_j = 1 \text{ to } 6pF \quad (7)$$

$$R_j > 10M\Omega \quad (8)$$

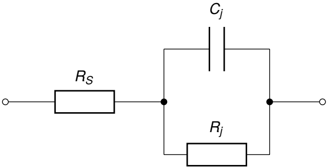


Figure 8 : Varactor diode AC equivalent circuit

Varactor Q

An important characteristic of any varactor diode is its Q factor. This is particularly important in tuned oscillator applications as a high Q varactor will result in a higher Q tank circuit which will in turn reduce the phase noise produced by the oscillator. Varactor Q is also very important in tuned filter applications as higher varactor Q will result in a sharper frequency response.

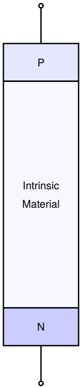
Considering the equivalent circuit of figure 8, we can write an approximate expression for varactor Q by ignoring R_j and considering the varactor as a series RC circuit, i.e. :

$$Q_v = \frac{1}{\omega_o C_j R_S} \tag{9}$$

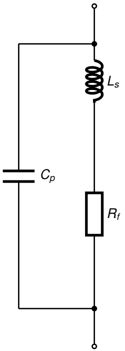
Aside from the obvious observation that Q can be increased by reducing the series resistance, R_S, (9) also reveals that there is a trade-off between capacitance and Q. Although in many applications we are inclined to select a varactor with the highest capacitance, we need to take into account the effect that the reduction in Q will have on the circuit.

The PIN Diode

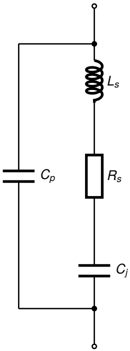
- PIN stands for (P-type)-Intrinsic-(N-type)
- PIN diodes are used as switches and attenuators
- Reverse biased - off
- Forward biased - partly on to on depending on the bias



(a) PIN diode construction



(b) PIN diode equivalent circuit - forward bias



(c) PIN diode equivalent circuit - reverse bias

Figure 9 : PIN diode structure and equivalent circuits

The PIN Diode : reverse bias

The admittance of the reverse bias equivalent circuit shown in figure 9(c) is as follows [20] :

$$Y_r = \frac{1}{R_s}\left[\frac{(f/f_{co})}{(f/f_{co})^2 + (1-(f/f_r)^2)^2}\right] + j\omega\left[\frac{C_j(1-(f/f_r)^2)}{(f/f_{co})^2 + (1-(f/f_r)^2)^2} + C_c\right] \quad (10)$$

Where :

$$\omega = 2\pi f$$

$$f_{co} = \frac{1}{2\pi R_s C_j}$$

$$f_r = \frac{1}{2\pi\sqrt{L_s C_j}}$$

f_{co} is the cut-off frequency of the diode and f_r is the reverse biased series resonant frequency of the diode. In practice, f_{co} is normally much higher than f_r. For example, using typical values from table **??** gives $f_{co} \approx 128GHz$ and $f_r \approx 12GHz$. We can therefore make the following approximation in relation to (10) [20] :

$$Y_r = \frac{1}{R_s}\left[\frac{(f/f_{co})}{1-(f/f_r)^2}\right]^2 + j\omega\left[\frac{C_j}{1-(f/f_r)^2} + C_c\right] \quad (11)$$

The PIN Diode : reverse bias

PIN diodes are generally selected so as to minimise the variation of device performance with frequency. In other words, devices are selected such that $(f/f_f)^2 << 1$ over the frequency range of operation. This leads to the further approximation:

$$Y_r \approx G_r + j\omega C_t \tag{12}$$

Where $G_r = (1/R_s)(f/f_{co})^2$ and $C_t = C_j + C_c$. The approximation (12) is very widely used, to the extent that manufacturers often specify C_t rather than C_j and C_c individually. When $f > f_r$ equation (11) indicates that the sign of the susceptance component becomes negative, meaning that the reverse biased PIN diode becomes inductive at higher frequencies.

The PIN Diode : forward bias

The admittance of the forward bias equivalent circuit shown in figure 9(b) is as follows [20] :

$$Y_f = \left[\frac{R_f}{R_f^2 + (\omega L_s)^2}\right] + j\left[\omega C_c - \frac{\omega L_s}{R_f^2 + (\omega L_s)^2}\right] \quad (13)$$

We can derive two approximations from (13) depending on the frequency range of operation. At low frequencies where $(\omega C_c) << 1/(\omega L_s)$, the impedance of the diode under forward bias conditions is :

$$Z_f = \frac{1}{Y_f} \approx R_f + j\omega L_s \quad (14)$$

At high frequencies, i.e. $R_f^2 << (\omega L_s)^2$, we can use the following approximation:

$$Y_f \approx \left(\frac{R_f}{\omega L_s}\right)^2 + j\left(\omega C_c - \frac{1}{\omega L_s}\right) \quad (15)$$

The PIN diode attenuator

- The above approximations can be employed in the design of a PIN diode attenuators.
- Figure 10 shows the schematic diagram of a simple shunt-connected PIN diode attenuator, comprising a PIN diode, a bias network, such as a choke inductor and decoupling capacitor, and two DC blocking capacitors, C_1 and C_2.
- At microwave frequencies, the PIN diode under forward bias appears essentially as a pure linear resistor, R_{rf}, whose value can be controlled by the DC bias. At low frequencies, the PIN diode behaves as an ordinary P-N junction diode.

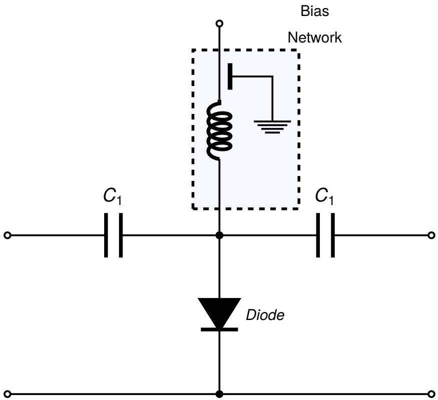


Figure 10 : PIN diode attenuator schematic

PIN diode attenuator : on state

Consider a shunt mounted PIN diode embedded in a transmission line system, of characteristic impedance Z_o.

In order to minimise the loss at the design frequency, f_o, we need to add an inductance L_p to resonate out the net capacitive reactance of the PIN diode, C_t. The value of this inductance is given by :

$$L_p = \frac{1}{(2\pi f_o)^2 C_t} \qquad (16)$$

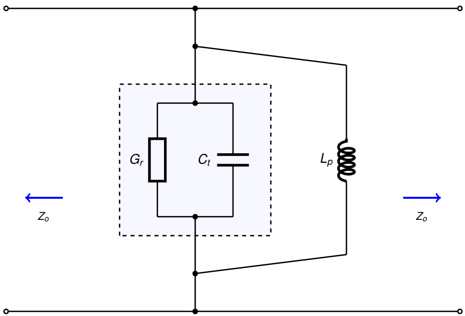


Figure 11 : PIN diode attenuator equivalent circuit : reverse bias ('on') state

PIN diode attenuator : on state

It can be shown that the insertion loss arising from the presence of any shunt admittance, $Y = G + jB$, in a transmission line of characteristic impedance, Z_o, is given by :

$$\alpha_{LY}(dB) = 10\log_{10}\left[\left(1 + \frac{GZ_o}{2}\right)^2 + \left(\frac{BZ_o}{2}\right)^2\right] \tag{17}$$

From (17) we can see that α_{LY} is at a minimum when $B = 0$, i.e. at resonance. With reference to figure 11, at resonance we have $G = G_r$ and $B = \omega C - 1/\omega L$, so the insertion loss of the circuit in figure 11 becomes:

$$\alpha_{on}(dB) = 10\log_{10}\left(1 + \frac{G_r Z_o}{2}\right)^2 \tag{18}$$

PIN diode attenuator : off state

- When the diode is forward biased, it will act as a short circuit across the transmission line, resulting in a high insertion loss. The switch will therefore be in the 'off' state.
- In order to minimise the shunt impedance across the transmission line in the forward biased case, we need to add a series capacitor, C_s to 'tune out' the effects of the series inductance L_s at f_o.
- The value of C_s is given by :

$$C_s = \frac{1}{(2\pi f_o)^2 L_s} \qquad (19)$$

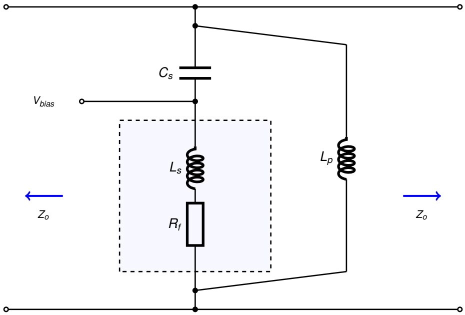


Figure 12 : PIN diode attenuator equivalent circuit: forward bias ('off') state

PIN diode attenuator : off state

From (17) we can derive the insertion loss α_H resulting from the presence of a shunt impedance $Z = R + jX$, as follows :

$$\alpha_{LZ}(dB) = 10\log_{10}\left[\left(1 + \frac{RZ_o}{2(R^2+X^2)}\right)^2 + \left(\frac{XZ_o}{2(R^2+X^2)}\right)^2\right] \qquad (20)$$

It can be shown that α_{LZ} is at a maximum when $X = 0$, i.e. at resonance. With reference to figure 12, at resonance we have $R = R_f$ and $X = \omega L_s - 1/\omega C_s$, so the insertion loss becomes:

$$\alpha_{off}(dB) = 10\log_{10}\left(1 + \frac{Z_o}{2R_f}\right)^2 \qquad (21)$$

From (18) and (21) we can see that, for a good quality PIN diode switch, i.e. one that has a low value of α_{on} and a high value of α_{off}, we need a high value of G_f in the reverse biased state and a low value of R_f in the forward biased state.

Tunnel diodes

- The Tunnel diode is basically a very highly doped *pn*-junction (around 10^{19} to $10^{20} cm^{-3}$) that makes use of a quantum mechanical effect called *tunnelling*. This type of diode is also known as an *Esaki diode* [1], after the inventor, Leo Esaki, who discovered the effect in 1957, a discovery for which he was awarded the Nobel Prize in Physics in 1973.
- As a consequence of the very high doping, a tunnel diode will have a very narrow depletion region, typically less than 10nm.
- The important point about the tunnelling mechanism, from the engineering point of view, is that it gives rise to a region of *negative resistance* in the I-V characteristic, shown as region '*B*' in figure 13. In region '*B*', an increase in forward voltage will result in a decrease in forward current, and vice versa.
- This is equivalent to saying that the device exhibits negative resistance in this region although, strictly speaking, we should call this negative dynamic resistance, as it refers to the negative slope of the V-I characteristics, not a physical 'negative' resistor, which does not exist, of course.

Tunnel diodes

- Tunnelling occurs in region '*A*'.
- Region '*C*' is the region of normal *pn*-junction behaviour.
- Region '*B*' can be considered as the region of transition between region '*A*', where the I-V characteristic is linear, and region '*C*' where the I-V characteristic obeys equation (5).
- As the bias voltage is increased from zero, the current increases linearly along curve '*A*' until a peak current is reached, at the bias voltage V_p. At this point tunnelling stops, at a current level called the *peak tunnelling current*, I_p in figure 13, also known as the 'Esaki current'.

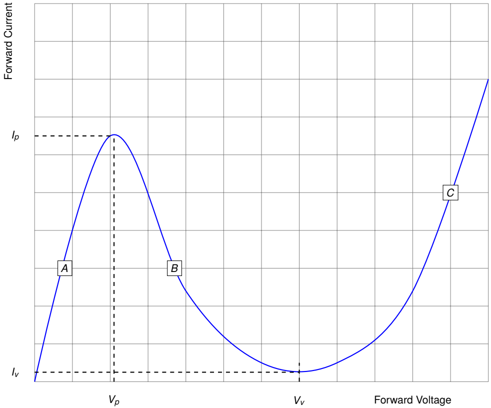


Figure 13 : Tunnel diode I-V characteristic

Tunnel diode circuit (load line)

We can analyse the circuit behaviour of a tunnel diode with DC bias with the aid of figure 14, from which, by inspection, we can write :

$$V_S = V_D - I_D R \quad (22)$$

The current through the diode is then given by :

$$I_D = \frac{V_D}{R} - \frac{V_S}{R} \quad (23)$$

Equation (23) is in the form of a straight line current/voltage graph with slope $(-1/R)$ and an intercept on the current axis of $(I_D = V_D/R)$. This is called a *load line*.

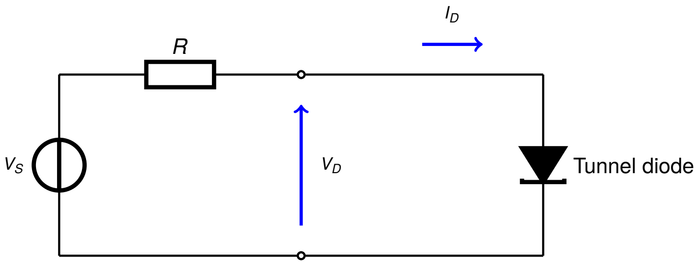


Figure 14 : Tunnel diode circuit

Tunnel diode circuit (load line)

- Point 2 is an unstable operating point, as any perturbations in bias voltage will cause the diode to jump from point 2 to either point 1 or point 3 on the load line. The circuit will therefore settle at either point 1 or point 3 depending on the history. It is in this mode that tunnel diodes are used as switched or memory devices.
- If the value of R, is reduced the load line will resemble load line-2 in figure 15. In this case the circuit has only one operating point, point 4. The total differential resistance is negative (because $R < |R_d|$). In this mode the diode can be made to oscillate at a microwave frequency dependent on the external L and C components.

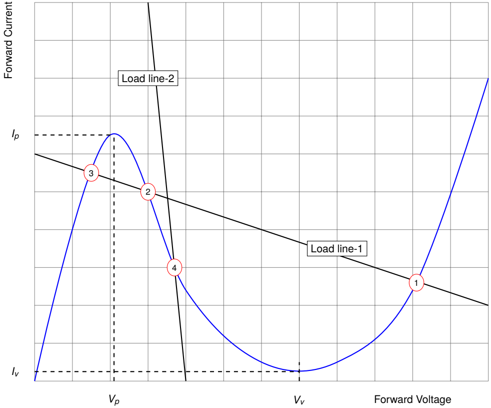


Figure 15 : Tunnel diode with a load line

The Gunn diode

- Simply a slab of N-type GaAs (Gallium Arsenide) with no PN junctions
- The band structure of certain compound semiconductors, such as GaAs and InP, has two local minima in the conduction band: one where the electrons have a low effective mass and a high mobility and a second local minimum at a higher energy level where electrons have a higher effective mass and a lower mobility [20, 17, 16].
- This causes a concentration of free electrons called a domain which moves through the device from Cathode to Anode.

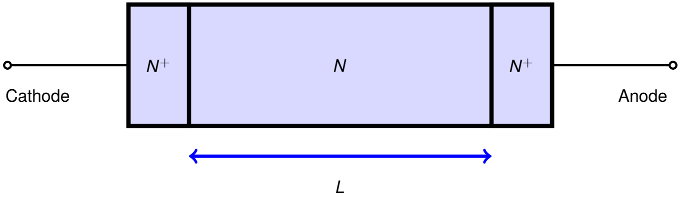


Figure 16 : Gunn diode construction

Gunn Diode Characteristic

- The drop in electron mobility with increasing electric field means that a sample of this material will exhibit a decrease in current with increasing applied voltage, that is to say a negative differential resistance.
- At higher voltages, the normal increase of current with voltage relation resumes once the bulk of the carriers are kicked into the higher energy-mass valley. Therefore the negative resistance only occurs over a limited range of voltages, as illustrated in figure 17.

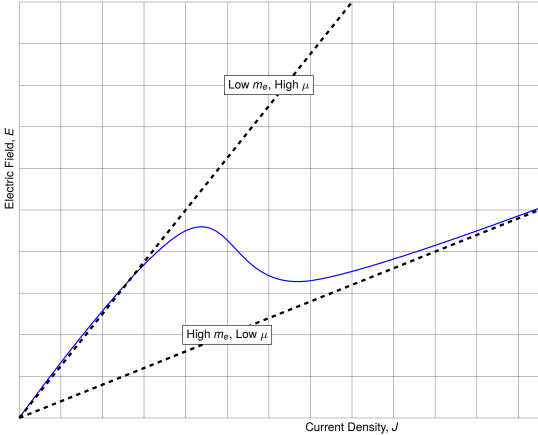


Figure 17 : Electric field/Current density characteristic for GaAs or InP

Gunn Diode Characteristic

The known time for formation of domains within the bulk material is given by [18] :

$$\tau_R = \frac{\varepsilon_o \varepsilon_r}{q n_o |\mu_-|} \qquad (24)$$

Where μ_- is the negative differential mobility in the material (typically $2,000 cm^2 V^{-1} S^{-1}$ for GaAs). The sample must be long enough to allow the domain to fully form before it reaches the opposite electrode, so we can say that, for a sample of physical length L, as shown in figure 16, we have the requirement:

$$\frac{L}{v_d} > \tau_R \qquad (25)$$

Where v_d is electron domain drift velocity. Combining (24) and (25) we have the following requirement for Gunn oscillation to take place:

$$n_o L > \frac{\varepsilon_o \varepsilon_r v_d}{q n_o |\mu_-|} \qquad (26)$$

The product of the carrier concentration and device length, $n_o L$, is an important figure of merit for a Gunn device and sets constraints on the physical size and doping level of the bulk semiconductor sample.

he corresponding frequency of oscillation is given by :

$$f = \frac{v_d}{L} \qquad (27)$$

Where v_d is the electron drift velocity in the semiconductor material, and is a function of temperature, doping and applied electric field.

Gunn Diode Characteristic

- The DC current voltage characteristic of a Gunn diode is shown in figure 18. Although superficially similar to the I-V characteristic of the tunnel diode shown in figure 13, it is important to remember that these two devices are based on totally different operating principles.
- One consequence of this is that Gunn diode oscillators can deliver much higher RF signal powers than tunnel diode oscillators.

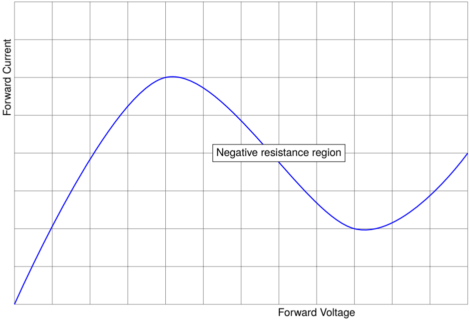


Figure 18 : Gunn diode I-V characteristic

Gunn Diode Oscillators

- A Gunn Diode can be used to construct an microwave oscillator simply by applying a suitable direct current through the device.
- In effect, the negative differential resistance created by the diode will negate the real and positive resistance of an actual load and thus create a "zero" resistance circuit which will sustain oscillations indefinitely.
- The oscillation frequency is determined partly by the physical properties of the Gunn device but largely by the characteristics of an external resonator.
- The resonator can take the form of a waveguide, microwave cavity or YIG sphere.
- Gallium arsenide Gunn diodes can operate up to 200 GHz, gallium nitride materials can reach up to 3 terahertz.

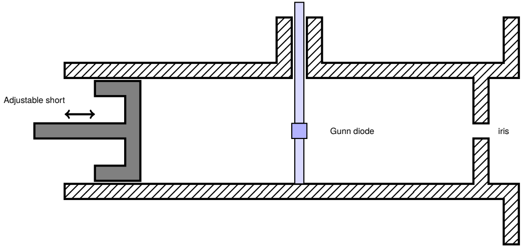


Figure 19 : GUNN diode waveguide oscillator

Gunn diode oscillators

- The AC equivalent circuit of a Gunn diode is shown in figure 20, where $-r$ represents the dynamic negative resistance of the device at a particular bias point.
- The same load line design methodology we introduced in the case of the tunnel diode can be applied to Gunn diode circuit design. The DC source, V, and external load resistor, R, are selected to give a load line that biases the device in the negative-resistance region.
- Inductance L arises from the wire leads, C is the effective capacitance of the device, and R_b is the bulk resistance of the device.

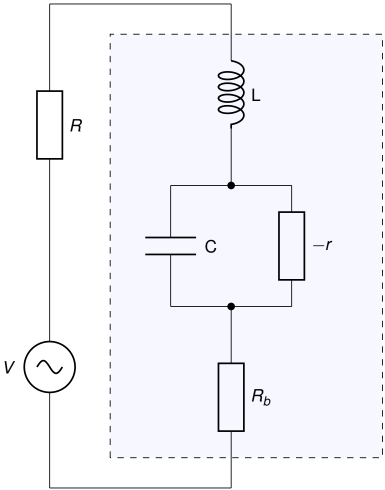


Figure 20 : GUNN diode AC equivalent circuit

Gunn diode oscillation conditions

The AC equivalent circuit of figure 20 can thus be analysed by writing the total impedance of the Gunn diode plus load as follows:

$$Z = j\omega L + \left(\frac{(-r)}{1 - j\omega Cr} \right) + (R_b + R) \qquad (28)$$

We now set the imaginary part of Z equal to zero, i.e. :

$$\left[\omega L - \frac{\omega C r^2}{1 + \omega^2 C^2 r^2} \right] = 0 \qquad (29)$$

Which defines the frequency of oscillation of the Gunn diode, ω_o, as :

$$\omega_o = \frac{1}{\sqrt{LC}} \sqrt{\left(1 - \frac{L}{r^2 C}\right)} \qquad (30)$$

The oscillation condition requires that the real part of Z be negative at ω_o. From (28), therefore, we have:

$$\frac{(-r)}{1 + \omega_o^2 C^2 r^2} + (R_b + R) < 0 \qquad (31)$$

Gunn diode oscillation conditions

Substituting (30) into (31) we obtain the condition for oscillation of the circuit in figure 20, given that r must be negative, as :

$$\frac{R_b + R}{r} < \frac{L}{r^2 C} < 1 \tag{32}$$

The requirement that $(R_b + R)/r < 1$ is equivalent to stating that the negative slope of the circuit load line must be greater than the slope of the negative-resistance curve, shown in figure 18.

Table of Contents

The IMPATT Diode

- IMPATT stands for Impact Avalanche And Transit Time Operates in reverse-breakdown (avalanche) region
- Applied voltage causes momentary breakdown once per cycle
- This starts a pulse of current moving through the device
- Frequency depends on device thickness (similar to Gunn)
- IMPATT diodes operate at frequencies between about 3 and 100 GHz.
- Main advantage : high power capability.
- Main disadvantage : high phase noise.

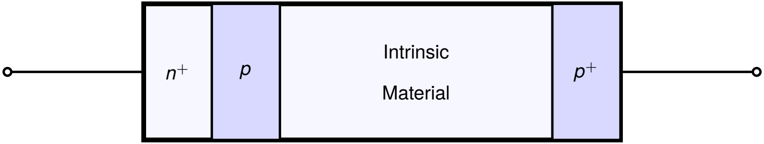


Figure 21 : IMPATT diode construction

Other IMPATT family members

A TRAPATT diode is similar to an IMPATT, having a structure p^+nn^+ or n^+pp^+. The acronym 'TRAPATT' stands for Trapped Plasma Avalanche Triggered Transit. The main difference in terms of performance is that the TRAPATT has a much higher DC to RF conversion efficiency when compared to the IMPATT (40 to 60 % [13], compared to 15 %[7]).

Other diodes in this family, having similar properties, include such devices as the 'BARRITT' diode (which stands for BARRier Injection Triggered Transit) [19] and the MITATT diode (which stands for Mixed Tunnelling and Avalanche Transit Time) [21]. What all these devices have in common is their application in high power microwave oscillators.

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