Chapter 10

Microwave Devices

10.0 Introduction

Several important high frequency application devices use the instabilities that occur in semiconductor. An important of the instabilities involves the *negative conductance*. Unlike the junction device, the electron involves in the microwave device has energy very much greater than the thermal energy. Thus, it terms as ‘hot’ electron. The energy of electron in positive conductance junction device is ‘warm’ electron because its energy is greater than the thermal energy. In positive conductance device, the voltage and current are in phase. They are anti-phase for negative conductance device. Three of the most commonly negative conductance devices are discussed here. They are the Esaki or tunnel diodes which depend on quantum mechanic tunneling, transit time diodes which depend on combination of carrier injection and transit time effect, and Gunn diodes which depend on the transfer of electron from a high mobility state to a low mobility state. All these devices can operate in negative conductance mode to provide amplification or oscillation at the microwave frequency.

10.1 Negative Conductance

The operation and performance of microwave diode can be understood by studying the response of charge fluctuation in an electronic system with negative resistance. In most case, the resistance of a material has positive value. If a local charge fluctuation is produced, it quickly "dies off" and it is not the case when it is in the negative conductance regime.

If a semiconductor of length $L$ and cross sectional area $A$ as a RC circuit, its resistance $R$ and capacitance $C$ shall be

$$ R = \frac{L}{en_0 \mu A} = \frac{L}{\sigma A} \quad (10.1) $$

$$ C = \frac{\varepsilon A}{L} \quad (10.2) $$
If a charge fluctuation develops in the semiconductor, it will decay with time constant RC. This time $\tau_d$ is called dielectric relaxation time, which is

$$
\tau_d = RC = \frac{\varepsilon}{en_0\mu}
$$

(10.3)

The fluctuation of charge $\Delta Q$ with response to time shall be

$$
\Delta Q = \Delta Q_0 \exp(-t/\tau_d)
$$

(10.4)

If the fluctuation of charge happened in a negative conductance material, which is having negative mobility $\mu$, then the charge fluctuation $\Delta Q$ with respect to time shall be

$$
\Delta Q = \Delta Q_0 \exp(t/\tau_d) = \Delta Q_0 \exp(L/(v_d\tau_d))
$$

(10.5)

where $v_d$ is the velocity of charge. From equation (10.5), it shall also mean that the charge fluctuation is growing instead of decaying.

There are two important cases to be considered for equation (10.5). For the case where $L < v_d\tau_d$, the structure can be used to amplify signal. For the case where $L > v_d\tau_d$, the structure can be used to generate microwave power. For first case the length $L$ of the structure is short such that growth of the fluctuation is not too large.

If the input signal is applied at the cathode side of the negative conductance structure shown in Fig. 10.1, the output of the structure would have amplified signal after it travels a distance $L$.

![Traveling charge amplification](image)

**Figure 10.1:** Traveling charge amplification
The structure will work only if the multiple integral of wavelength $\lambda$ of the signal is equal to length $L$. i.e.

$$L = n\lambda = n\frac{2\pi}{k}$$  \hspace{1cm} (10.6)

where $k$ is the wave vector.

This shall also mean that

$$\omega_s = n^2\pi f_{tr}$$  \hspace{1cm} (10.7)

where $f_{tr}$ is the transit time frequency which is equal $v_d/L$. For condition that $L < v_d\tau_d$, it can be expressed as $\frac{L}{\tau_d V_d} < 1$ or $n_a L < \frac{eV_d}{ck}$. For GaAs, this gives a condition on the carrier concentration-length product $n_a L \leq 1.19 \times 10^{12} \text{cm}^{-2}$.

**10.2 Tunnel Diode**

As mentioned earlier, Esaki or tunnel diode operates in a certain region of the I-V characteristic curve of a $pn$ junction that made from degenerate semiconductor by quantum mechanical tunneling. The characteristic curve of the tunnel diode is shown in Fig. 10.2.

![Characteristics curve of tunnel diode](image)

**Figure 10.2:** Characteristic curve of tunnel diode
The energy band diagrams showing the activities of various parts of the characteristic curve are shown in Fig. 10.3.

Figure 10.3: Energy band diagrams showing the activities of different parts of the characteristic curve

Figure 10.3(a) shows the zero bias voltage equilibrium state of the $pn$ junction which comprising of two degenerate semiconductors. When a reverse biased voltage is applied to the $pn$ junction, electrons from filled state of $p$-region are tunneling through the depletion region to empty state of $n$-region as shown in Figure 10.3(b). As the reverse biased voltage increases, more tunneling electron occur which constitute current shown in third quadrant of I-V characteristic curve. When the forward biased voltage is applied to the $pn$ junction, the electrons from filled state of $n$-region begin to tunnel through the depletion region to the empty state of $p$-region as shown in Fig. 10.3(c). This constitutes
the increase of current shown in the first quadrant of I-V characteristic curve. As the forward biased voltage increases, the tunneling electrons are lesser and lesser which constitute the drop of curve in the first quadrant of I-V characteristic curve. When more forward bias voltage is applied, majority electrons begin to move from $n$-region to $p$-region and majority holes begin to $p$-region to $n$-region as shown in Fig. 10.3(d). This forms the forward bias current of a normal diode.

10.3 Transit Time Devices

Transit time negative conductance microwave device operates by combination of carrier injection and transit time effect. $PN$ junction of simple structure or variation of structure is biased to achieve tunneling or avalanche breakdown, with an ac voltage riding on dc bias. The generated carriers are swept through drift region to the terminal of the device. ac current of 180° out of phase with the applied ac voltage can be achieved with proper bias condition and device structure. The device can convert dc to microwave ac signals with high efficiency and is very useful in the generation of microwave power for many applications.

We shall discuss a few of transit time device such as the impact avalanche transit time device IMPATT diode, quantum-well injection transit time QWITT diode, and trapped plasma avalanche triggered transit TRAPATT diode here.

10.3.1 IMPATT Diode

The device operates by injection of carrier into the drift region is called impact avalanche transit time IMPATT diode. The Read diode as shown in Fig. 10.4 is best example to illustrate the basic operation of the IMPATT device. The device has $n^+p-i-p^+$ structure, where $i$ is the intrinsic semiconductor. The $n^+p$ region is reverse-biased to get avalanche breakdown and drift the hole toward $p^+$ terminal. A similar device $p^+n-i-n^+$ can be built which can take advantage of the high electron mobility as compared with hole.

Essentially the IMPATT diode operates in a negative conductance mode when the ac component of current is negative over a portion of the cycle during which the ac voltage is positive and vice versa. The negative conductance occurs because of two reasons that causing the current to lag behind the voltage in time. It is due to delay of avalanche process and transit time of the carrier in the drift region. If the total delay time is approximately half cycle of the
operating frequency, a negative conductance occurs and the device can be used for oscillation and amplification.

![Diode Configuration and Electric Field](image)

**Figure 10.4:** A Read diode configuration and its electric field

The process of the time dependence of the growth and drift of the holes during a cycle of applied voltage is shown in Fig. 10.5. If the device is dc biased such that the critical field $E_{\text{crit}}$ is just met for avalanche to occur in the $p^+n$ depletion region, the avalanche multiplication at begins at time $t = 0$ as shown in Fig. 10.5(a). As ac voltage goes positive cycle, more and more holes are generated in the depletion region since the electric field is greater than the critical electric field $E_{\text{crit}}$ as shown in Fig. 10.5(b). The hole current is also shown to be increase exponentially as dotted sketch and drift toward the $p^+$-region. The hole current will reach its maximum at the end of positive ac cycle. During the negative ac cycle, the electric field is less than the critical electric field $E_{\text{crit}}$ as shown in Fig. 10.5(d). The avalanche multiplication is halt but the hole current is continuing to drift toward the $p^+$-region.

If the length of the drift is chosen in such the hole pulse is collected at the $p^+$-region at the end of one ac cycle, then hole pulse cycle will repeat and its transit time would be

$$\frac{L}{v_d} = \frac{T}{2} = \frac{1}{2f} \quad (10.8)$$

where $v_d$ is the drift velocity of hole, $T$ is period of the applied ac, and $f$ is frequency of the applied ac.
If the drift velocity of the hole is $1.0 \times 10^7 \text{ cms}^{-1}$ and the thickness of the drift region is $5 \times 10^{-4} \text{ cm}$, then the optimum operating frequency for the device is $1.0 \times 10^7 / (2 \times 5 \times 10^{-4}) = 1.0 \times 10^{10} \text{ Hz}$. Negative conductance for the device would exhibit for frequencies above and below this optimum frequency for exact $180^0$ phase delay.

Figure 10.5: Time dependence of the growth and drift of hole for Read diode
Other simpler structure such as \textit{pn} junction or \textit{p-i-n} junction can be used as the IMPATT diode. Particularly, the \textit{p-i-n} diode where the applied voltage drops across the \textit{i}-region serves as a uniform avalanche region and also the drift region.

### 10.3.2 QWITT Diode

The major setback of IMPATT diode for high frequency operation is the fact that the avalanche process depends on the random impact ionization, which given rise to inherent noise. Thus, a new approach for injection carrier is necessary. This problem was overcome by using quantum-well injection discovered by V. P. Keseran from the University of Texas. The device is called \textit{quantum-well injection transit time} QWITT diode as shown in Fig. 10.6.

![QWITT diode structure and its energy diagram](image)

The device structure consists of a single GaAs quantum well between two Al_{x}Ga_{1-x}As barriers, in series with a drift region of undoped GaAs. When the voltage across the well equals to \(2E_1/e\), a large peak current through the device occurs as shown in Fig. 10.7. Thus, in QWITT diode, maximum resonant tunneling of electron through the well can be achieved if the dc bias voltage is adjusted so that it satisfies the condition as shown in Fig. 10.8, which is the expression shown in equation (10.9).

\[
2E_1/e = V_o \sin \omega t + V_1 \tag{10.9}
\]
where $V_o$ is the amplitude of ac voltage across the quantum well and $V_1$ is the effective dc voltage across the well and $E_1$ is the energy level in the well.

If an appropriate bias is applied so the Fermi level in $n^+$-GaAs is below the energy level $E_1$ by the amount $V_o$ and an ac signal $V_o \sin \omega t$ is riding on this bias, then the resonant tunneling of electron through the well will peak at the injection angle of $\pi/2$ as shown in Fig. 10.8. The electron will then traverse through the drift region at their saturation velocity resulting in a dynamic negative resistance.

The QWITT diode can also be biased to move the Fermi level in the $n^+$-GaAs above the energy state in the GaAs well so that the current injection peaks
around $3\pi/2$ in the negative half of the ac voltage cycle. Compared to injection near $\pi/2$, this mode should have higher efficiency, since electron in at $3\pi/2$ drift while $V_o$ voltage is negative. No other transit-time device exhibits an injection angle of greater than $\pi$. The energy band diagram showing voltage across the quantum well is in resonance at $\omega t = \pi/2$.

![Energy band diagram of QWITT diode showing voltage across quantum well resonance at 90° of the ac cycle](image)

**Figure 10.9:** Energy band diagram of QWITT diode showing voltage across quantum well resonance at 90° of the ac cycle

### 10.3.3 TRAPATT Diode

The highly efficient mode of operation for a transit time device is shown in QWITT diode. If a large current suddenly applied to the sample, the displacement current $\varepsilon dE/dt$ can be so large that the electric field $E$ is greater than the critical field $E_{\text{crit}}$. Thus, it propagates faster through the device than the maximum carrier velocity. Therefore, an avalanche zone moves through the $i$-region, filling it with an electrostatically neutral electron-hole population or plasma. The plasma is created very rapidly before the carriers have a chance to drift appreciably. The presence of these carriers in large numbers greatly reduces the terminal voltage across the diode. The electron-hole plasma collapses as hole drifts to the right and electron drift to the left. As EHP plasma is depleted during recovery transient, the terminal voltage builds up a high value and the current goes toward a low value. In proper resonant circuit, the cyclic buildup and discharge of plasma gives rise to efficient microwave power generation. Since the electron-hole plasma is initiated during the transit of an avalanche zone, the type of operation is generally called TRAPATT cycle or TRApped Plasma Avalanche Triggered Transit.
10.4 The GUNN Effect Device

Microwave device operates by transferred electron mechanism is called GUNN diode named after JB Gunn who first demonstrated one form of oscillation. In the transferred electron mechanism, the conduction electron of the semiconductor is transferred from a state of high mobility to a state of low mobility by influence of strong electric field. Negative conductance operation can be achieved in the diode for which the mechanism applies and the result is useful in microwave circuit.

According to Ridley-Watkins-Hilsum theory, the band structure of a semiconductor must satisfy the following three criteria in order to exhibit negative conductance.

1. The separation energy between the bottom of the lower valley and the bottom of the upper valley must be several times larger than the thermal energy at the room temperature which shall mean $\Delta E > kT$.
2. The separation energy between the valleys must smaller than the band-gap energy between conduction and valence bands, which shall mean $\Delta E < E_G$. Otherwise, the semiconductor will breakdown to become high conductive device before electron can be transferred.
3. Electron in the lower valley must have high mobility, small effective mass and a low density of state, whereas those in upper valley must have low mobility, large effective mass, and high density of state. In other word, electron velocity $dE/dk$ must be larger in lower valley than in upper valley.

Based on these criteria, silicon and germanium are not the materials for microwave device. Compound semiconductor such as gallium arsenide GaAs, indium phosphide InP, and cadmium telluride CdTe satisfy the criteria. Other example compound semiconductors that do not satisfy the criteria are indium antimonide InSb, gallium phosphide GaP, indium arsenide InAs.

10.4.1 Transferred Electron Mechanism

As it has been mentioned in Section 3.2, the mobility of most semiconductors would not be linear at high electric field. It would reach its scattering limited velocity. The energy of the electron can be raised by an applied electric field to the material such that it is transferred from one region of the conduction band to another higher energy region as shown in Fig. 10.10, the $E-k$ diagram of GaAs.
The electron will remain at higher energy level at $L$ valley as long as the electric field is greater than the critical field $E_{\text{crit}}$.

Figure 10.10: $E$-$k$ diagram of GaAs showing central $\Gamma$ valley and satellite $L$ valley

For low electrical field, the electron resides in the lower $\Gamma$ valley of conduction band and the mobility $\mu_\Gamma = \nu_d/E$ is high and constant. However, at Satellite $L$ valley, the mobility $\mu_L$ is low, drift velocity is low, and electrical field is high. Thus, in between two states, there is a region of negative slope on the drift velocity $\nu_d$ versus electrical field $E$ as shown in Fig. 10.11. $\mu^*$ is the average negative differential mobility during transition.

Figure 10.11: A possible characteristic curve electron transfer from lower energy level to higher energy level in conduction band
The plot of electron drift velocity versus electric field for GaAs and InP is shown in Fig. 10.12. The drift velocity of the electron reaches its maximum drift velocity before it is transferred from $\Gamma$ valley to $L$ valley, whereby the drift velocity begins to drop as electric field increases.

The existence of a drop in mobility with increasing electric field and resulting possibility of negative conductance were predicted by Ridley and Watkins and by Hilsum several years before Gunn demonstrated the effect in GaAs. The mechanism is often called the Ridley-Watkins-Hilsum mechanism. The negative conductivity effect depends only on the bulk properties of the semiconductor and not on junction or surface effect. It is therefore called bulk negative differential conductivity BNDC effect.

Figure 10.12: Electron drift velocity versus electrical field plot for GaAs and InP at temperature 300K

10.4.2 Formation and Drift of Space Charge Domain

If a sample of GaAs is biased such that the electrical field falls in the negative conductivity region, which is about 3,000V/cm times the thickness of GaAs diode then a space of instability is resulted and the device cannot be maintained in a dc stable condition. A small accumulation of electron will create a dipole, which is called domain formed near the cathode reduces the electric field for the rest of material and causes the current to drop to about two-thirds of it maximum value. The space of domain will grow exponentially with time following $Q(t = 0)\exp(t/\tau_d)$ as it drifts from cathode to anode, which is illustrated in Fig. 10.13.
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When the dipole is created and separated by a distance d, the electric field within the dipole is higher than either left or right side of dipole. Owing to negative differential resistance, the current at the low field side is higher than the high field dipole.

![Space Charge](image)

**Figure 10.13:** Build-up and drift of space charge domain in negative conductance region of GaAs when it is subjected to velocity-electric field as shown in Fig. 10.12

10.4.3 Operations of Transfer Electron Device

Transfer electron device TED can be used to generate microwave oscillation when \( n_0L \) value is \( 10^{12} \text{cm}^{-2} \leq n_0L < 10^{14} \text{cm}^{-2} \) and amplify microwave signals when \( n_0L \leq 10^{12} \text{cm}^{-2} \). If the device is doped lightly or is short, it can be used as traveling wave amplifier. If the device is highly doped or is long, it can be used as oscillator. Depending on its doping and length, TED can operate in one of the four modes, which are amplification mode - *accumulation layer mode* and oscillation mode - *transit time mode*, *quenched domain mode*, and *limited space-charge accumulation mode*.

10.4.3.1 Accumulation Layer Mode

If the device satisfies \( n_0L < 10^{12} \text{cm}^{-2} \) condition and if it is connected to a resonant circuit, it can oscillate in the accumulation layer mode. The voltage across the device is always above the threshold value, so that the negative resistance exists over the entire device at all times. The waveform generated is not ideal. Indeed this is amplification mode. The efficiency is about 5% for GaAs and about 7.5% for InP.
10.4.3.2 Transit Time Mode

The device has domain drift velocity $v_d \cong 1 \times 10^7 \text{cm/s}$ or $n_o L > 10^{12} \text{cm}^{-2}$. The space charge layer starts to increase exponentially in time and the dipole domain starts to move towards the anode. As the dipole grows, more of the applied potential falls across the dipole. As the result, once the domain acquires a certain size and no other region in the sample has negative resistance. Thus, there is only one domain has negative resistance that can travel to the anode. After this the next domain begins to form at cathode. This mode of operation produces current spike at the output. The frequency shall be $v_d/L$, which low and the efficiency is about 10% for GaAs and 15% for InP.

10.4.3.3 Quenched Domain Mode

For this mode, the device has $v_d > 2.0 \times 10^7 \text{cm/s}$ $n_o L > 10^{12} \text{cm}^{-2}$ but the bias voltage is adjusted to a different value. The bias voltage is adjusted to support the start of the domain instead of the bias voltage is dropped across the high field domain in the transit time mode. At some voltage $V_s$, which is smaller than $V_{\text{crit}}$, the domain width goes to zero. Thus, the domain is quenched before it reaches the anode. The $V_s$ voltage also allows the domain to move to saturation voltage. The collapse of the domain raises the voltage above $V_{\text{crit}}$ that allows a new domain to forms. In this manner, higher frequency is achieved. The efficiency is 13% for GaAs and 20% for InP. The period of oscillation is $\tau_f < \tau_o$ such as $1.5 \tau_f = \tau_o$.

10.4.3.4 Limited Space-Charge Accumulation LSA Mode

For this mode, the device has $v_d > 2.0 \times 10^7 \text{cm/s}$. If the frequency of the resonant circuit is very high, the domains do not have a chance to form during the time the field is above critical voltage. As the RF signal is above the critical voltage, the space charge domain begins to form. However, since the radio frequency is high, the field switches below threshold causing charge to dissipate. The LSA mode is the simplest mode of operation and consists of a uniformly doped semiconductor with minimum imperfections. The efficiency of LSA mode can reach 20% for GaAs. The period of oscillation is $\tau_f < \tau_o$ such as $3 \tau_f = \tau_o$.

10.4.4 Parameters of Transfer Electron Device

The ratio of density of state of electron in $L$-valley $N_L$ and $\Gamma$-valley $N_\Gamma$ for semiconductor follows equation (10.10).
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\[ \frac{N_L}{N_\Gamma} = 3 \left( \frac{m_L^*}{m_\Gamma} \right)^{3/2} \]  \hspace{1cm} (10.10)

The fraction of electron density \( n_L \) in \( L \)-valley to density of electron \( n_\Gamma \) in \( \Gamma \)-valley for semiconductor is

\[ \frac{n_L}{n_\Gamma} = \frac{N_L}{N_\Gamma} \exp \left( -\frac{\Delta E}{kT} \right) = 3 \left( \frac{m_L^*}{m_\Gamma} \right)^{3/2} \exp \left( -\frac{\Delta E}{kT} \right) \]  \hspace{1cm} (10.11)

The negative conductance property will disappear if the electron velocity \( V \) at the critical field \( E_{\text{crit}} \) approaches the electron saturation velocity \( V_s \). The velocity is given by equation (10.12).

\[ V = \left( \frac{n_L \mu_{\text{ef}} + n_\Gamma \mu_{\text{el}}}{n_\Gamma + n_L} \right) E_{\text{crit}} \]  \hspace{1cm} (10.12)

where \( \mu_{\text{ef}} \) and \( \mu_{\text{el}} \) are mobility of electron in \( \Gamma \)-valley and \( L \)-valley respectively. From equation (10.12), the fraction of electron density in \( L \)-valley at saturation velocity \( V_S \) is

\[ \left. \frac{n_L}{n_\Gamma} \right|_{v = V_S} = \frac{\mu_{\text{el}} - \frac{V_S}{E_{\text{crit}}}}{\frac{V_S}{E_{\text{crit}}} - \frac{\mu_{\text{ef}}}{}} \]  \hspace{1cm} (10.13)

From equation (10.11) and (10.13), the temperature \( T_{\text{crit}} \) for which the device cannot be operated as negative conductance device is

\[ \frac{\mu_{\text{el}} - \frac{V_S}{E_{\text{crit}}}}{\frac{V_S}{E_{\text{crit}}} - \frac{\mu_{\text{ef}}}{}} = 3 \left( \frac{m_L^*}{m_\Gamma} \right)^{3/2} \exp \left( \frac{-\Delta E}{kT_{\text{crit}}} \right) \]  \hspace{1cm} (10.14)

The equation shows that the GUNN diode cannot operate above temperature \( T_{\text{crit}} \). Indeed GUNN effect negative conductance is much reduced for temperature 200 to 300K below this temperature \( T_{\text{crit}} \).

**Exercises**

10.1. Calculate the time constant for decay of a charge fluctuation in GaAs of doping concentration is \( 5 \times 10^{15} \text{ cm}^{-3} \) at a low electric field where electron mobility is \( 8,500 \text{ cm}^2/\text{V-s} \).
10.2. Describe the operating principle of tunnel diode using its I-V characteristic curve.

10.3. State the conditions for a homogenous semiconductor device to exhibit negative conductance.

10.4. Given the band structure of indium arsenide and indium phosphide semiconductors. Determine and state the reason if they will exhibit negative conductance.

10.5. Describe the operating principle of IMPATT diode and under what condition a peak electron current can be obtained with ac voltage for a $p^+n-i-n^+$ IMPATT diode?

10.6. Describe how a negative mobility can possibly happen for a GUNN diode.

10.7. A typical $n$-type GaAs Gunn diode has threshold field 2,800V/cm, applied field 3,200V/cm, device length 10$\mu$m, doping concentration $2.0 \times 10^{14}$ cm$^{-3}$ and operating frequency 10GHz. Calculate the electron drift velocity, current density, and estimate its negative mobility.

10.8. For $n$-type GaAs semiconductor has doping concentration $3.5 \times 10^{16}$ cm$^{-3}$, $\mu_L = 500$ cm$^2$/V-s and $\mu_\Gamma = 8,500$ cm$^2$/V-s, and the effective mass of
electron in $L$ valley and $\Gamma$-valley are respectively equal to 0.22 and 0.067. Calculate density of electron at in $L$-valley at temperature 358K.

10.9. Calculate the temperature for which $n$-type InP semiconductor looses its negative conductance property. It has doping concentration $5 \times 10^{16} \text{cm}^{-3}$, effective electron mass at $L$-valley and $\Gamma$-valley are 0.325 and 0.077 respectively, and the mobility at $\Gamma$-valley and $L$-valley are 4.600 cm$^2$/V-s, and 250 cm$^2$/V-s respectively, $\Delta E = 0.69$eV, and electron saturation velocity $9.2 \times 10^6$cm/s. Note: Use figure 10.12 to obtain the critical electric field.

Bibliography

