COMPUTER ANALYSIS FOR DESIGNING NARROW-BAND TUNNEL DIODE AMPLIFIER CIRCUIT

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ABSTRACT

The purpose of this paper is to shed further light on the operating characteristics and limitations of tunnel diode amplifier circuits, particularly those with different doping concentrations. This has been achieved by developing efficient and economical computer programs which incorporate all of the important material parameters and doping levels in an exact manner. These computer programs are then employed to study the properties of tunnel diodes in high frequency amplification circuits. Some very interesting properties of these devices and the effects of material parameters and doping levels on their performance are presented and discussed. This leads to a better understanding of these devices and their limitations. Preliminary calculations have also been carried out on different GaAs and InSb tunnel diodes and the results are presented. Experimental measurements of the characteristics of the amplifier show good agreement with those obtained theoretically.

INTRODUCTION

The tunnel diode invented by "Leo Esaki" in 1958 [1], is a device that can function efficiently either as an amplifier or an oscillator. It is a pn-junction in which both the n- and p-regions are heavy doping conditions; the contact potential is large; the space-charge region is very narrow and the field in this region is extremely high [2-4]. The aim of this work is to suggest a computer program to solve the general equations for the devices and to introduce the effect of device physical parameters, circuit terms, operating conditions upon their performance as a high frequency amplifier, as well as, to compare the calculated results with those obtained experimentally.

Static Parameters of Tunnel Diode

Tunnel diodes belong to the devices exhibiting a negative differential conductance (NDC) which enables the tunnel diodes to amplify and

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generate signals [5]. The tunneling current is proportional to the number of overlapping energy levels in the valence band and in the conduction band of the p–and n–type materials. In the forward biased junction, the Fermi level becomes 5% shifted that, opposite the vacant levels in the valence band of the p–region there develop filled levels in the conduction band of the n–region with the result that the tunneling current of electrons flows across the pn–junction from the n–region to the p–region. This current will continue increasing to its highest value until the overlapping reaches a maximum. The maximum overlap sets in, when the forward voltage.

\[ V_P = \frac{(E_{Fn} + E_{FP})}{3} q \]  

(1)

As the voltage is further increased, the number of overlapping levels decreases and at the voltage:

\[ V_V = \frac{(E_{FP} + E_{Fn})}{q} \]  

(2)

this number goes to zero and the current flowing through the diode reduces now to a minimum. At voltages above (\(V_V\)), the usual forward diffusion current passes through the pn–junction, which continues to grow with increasing voltages (Fig. 1). Voltages (\(V_P\)) and (\(V_V\)) depend on the values of (\(E_{FP}\)) and (\(E_{Fn}\)), i.e., on the degree of doping of the p–and n–region of a semiconductor [6]. Valley current, also called excess current, depends on the density of levels in a semiconductor band gap, which are responsible for the presence of the tunneling current at voltages higher than (\(V_V\)). The larger the number of energy levels in the band gap, the higher the valley current. On the other hand, voltage (\(V_{FP}\)) depends on the width of a semiconductor band gap.

A major property exhibited by the tunnel diode, allowing it operate as an active element of the circuit, is a differential negative resistance which develops at voltage \(V > V_P\). Its value is determined from the empirical formula.

\[-R_o \text{ (ohm)} = \frac{200}{I_p} \text{ (for GaAs–diodes)} \]  

(3)

and the diode will function as an amplifier when the condition \(| R_o^- | > | R_L |\) is satisfied. Otherwise, the stability of the tunnel diode negative resistance will become dependent on the external resistance.

**Tunnel Diode Dynamic Parameters**

Two dynamic parameters [6–8] which are useful in the selection of tunnel diodes for different applications are the resistive cut–off
frequency (F₀) and the self resonant frequency (Fₚ). Their values are given when the total series impedance of the tunnel diode equivalent circuit is considered. The input impedance of the equivalent circuit of the tunnel diode, at high frequency [7], across the terminals "a", "b" is as shown in Fig. (2).

\[ Z = R_s - \frac{R_o}{1 + (wC_D R_o)^2} + Jw \left( L_s - \frac{C_D}{(1/R_o)^2 + (wC_D)^2} \right). \] (4)

where:

- \( R_s \) : Total series resistance,
- \( L_s \) : Self inductance of leads,
- \( C_D \) : Diffusion capacitance.

The cut-off frequency is the frequency above which the real part of the diode impedance is positive. Equating the real part of Equ. 4 to zero, the cut-off frequency is obtained [5].
\[ F_e = \frac{1}{2\pi C_D R_0} \sqrt{\frac{R_0}{R_s} - 1} \]  

(5)

On the other hand, self-resonant frequency \( (F_r) \) of the tunnel diode is the frequency of resonance of the inductive reactance and the capacitive reactance and is given by equating the imaginary part of Eqn. 4 to zero, then:

\[ F_r = \frac{1}{2\pi C_D R_0} \sqrt{\frac{C_D R_0^2}{L_s} - 1} \]  

(6)

The effective negative resistance \( (R_o^-) \) displayed by a given tunnel diode in a circuit depends on the operating frequency \( (F_o) \). Its value calculated from the \((I-V)\) characteristics by using incremental dc-values, does not consider the shunting effect of the inherent capacitance \( (C_D) \) of the diode. The following equation permits calculation of the effective negative resistance at any particular operating frequency \([5]\).

\[ R_o^- = \frac{R_o}{1 + (2\pi F_o C_D R_0)^2} \]  

(7)

Experimental Procedures:

1. De- Characteristics

In order to investigate the factors that affect the gain of tunnel diode amplifier, six different types of GaAs tunnel diodes namely:
3N301B, AN301r, Au301A, AN301Г, AN301σ and AN301A were subjected to several tests in order to plot their output characteristics. Besides, device material effects was also considered applying InSb tunnel diode; type ТГ. Tektronics 577–177–D1 storage curve tracer, which is a dynamic component tester was used in plotting the device characteristics.

2. Amplifier Circuit Analysis

The tunnel diode [9, 10] can often be used as the active element in a conventional amplifier circuit. Since the tunnel diode is a two-terminal device it does not supply the isolation of either the vacuum tube or the transistor. Thus, special techniques must be used when cascading tunnel–diode amplifiers. For convenience, voltage amplification will be discussed although a similar discussion could be applied to current–or power–amplification.

In order to determine the voltage gain of the circuit amplifier using different tunnel diode types, the simple circuit shown in Fig. (3) is presented. The experimental values of the circuit parameters were chosen according to theoretical calculations for obtaining the optimum conditions of the voltage gain of the circuit amplifier. They are: \( L_1 = L_c = L_C = 25 \mu \text{H}, C_C = 1000 \text{ pF, and } R_L = 10 \text{ k. ohm.} \)

![Fig.(3)A Simple Tunnel-Diode Amplifier.](image)
RESULT AND DISCUSSION

DC-Characteristics

Fig. (4) illustrates the (I–V) characteristics of two different tunnel diodes. Interesting feature of the two curves is the presence of the “NDC” region. This “NDC” devices can be used either as amplifier or oscillator in a wide spectrum of electronic systems. The physical basis [11, 12] for for amplification is due to that, when a signal is applied to a circuit element of a “NDC” character, the current produced is opposite to the field, hence energy absorbed from the element and the signal field is amplified.

![Graph of current vs voltage for two different tunnel diode types.](image)

**Fig. 4:** Characteristics for two Different Tunnel Diode Types.

Response Characteristics

The dependence of the gain on the frequency was plotted at an input signal amplitude of 20 mV in the frequency range from 1 to 10 MHz. Moreover, the amplitude characteristics were measured at the frequency of the peak gain. Fig. (5a) shows the variations of the am-
Efficiency gain (A) with the frequency of the input signal (F) for the Au301A GaAs sample. It is clear that, the gain of the amplifier increases as a function of the input frequency, reaching a peak value, then decreases at higher frequencies (narrow band amplifiers). Fig. (5b) shows the amplitude characteristics for the tunnel diode amplifier at the frequency of the peak gain, where a linear relationship between input and output signals, with a correlation coefficient of 0.99975, was achieved.

Fig. 5: (a) Gain-Frequency Dependence and (b) Amplitude Characteristics for the Amplifier.

Effect of Device Parameters

The gain of the tunnel diode amplifier was shown to increase as a function of its negative- and minimum negative-resistance (Rn) values, the extracted power level, peak current, the currents ratio, valley voltage, and forward peak voltage. On the other hand, the increase in the device valley current values, the VD/VF ratio and voltage swing are shown to cause pronounced decrease in the gain value. Such results are in good agreement with the theoretical expectations mentioned earlier.

Effect of Device Material

The effect of the device material on the amplifier response characteristics were obtained theoretically and experimentally for both the diode type Au301A (GaAs) and Yt (InSb). The peak gain point of the two devices occur at different frequencies (Fig. 6). Also, the gain was shown to be with different amplitudes. The gain obtained for GaAs samples shows higher value than that value, either measured or calculated, for InSb samples. For all the tested devices, the peak gain for
GaAs diodes occur at higher frequency values. The variations in the
gain amplitude of devices with different material types is attributed to
the variation in the GaAs current vbe, which is a function of the
impurity concentration and the junction area, energy gap and electrical
parameters.

![Graphs showing theoretical and experimental results.]

Fig. 6: Theoretical (a) and (b) Experimental Results Showing the Effect of the Device Ma-
terial on the Gain.

**Effect of Circuit Parameters**

a) L<sub>s</sub> and C<sub>s</sub>

Theoretical and experimental investigations were carried out in
order to analyze the effect of the circuit parameters on tunnel diode
amplifier characteristics. The values of the circuit capacitor (C<sub>s</sub>) and
inductor (L<sub>s</sub>) were chosen to get the maximum gain [9, 11-14]. They
were calculated at the operating input frequency of 1 MHz. Fig. (7)
shows the effect of varying the values of the circuit parameters (L<sub>s</sub>)
and (C<sub>s</sub>) on the calculated gain at different normalized frequency values.
It is clear from the figure that the gain is higher (3.6) as (L<sub>s</sub>) takes
the value of 125 μH, and C<sub>s</sub> is 200 pF. On the other hand, the gain is
lower as L<sub>s</sub> = 2.5 μH and C<sub>s</sub> = 10000 pF. Although the product of
(L<sub>s</sub>) and (C<sub>s</sub>) is constant (3.5 x 10<sup>-10</sup>) for all cases, yet the value of the
gain higher or lower, depends on the chosen values of circuit elements
(L<sub>s</sub>) and (C<sub>s</sub>). Also, the shape of the calculated gain was shown to be
function of both (L<sub>s</sub>) and (C<sub>s</sub>) values. The gain has sharp peaks for
(L<sub>s</sub>) values greater than 50 μH but less than 250 μH. On the other
hand, the capacitor (C<sub>s</sub>) has values greater than 100 pF and less than
500 pF. They were so that, because of their impedances. The gain has no peaks for \( L_c \) less than 5 \( \mu \)H and \( C_c \) higher than 5000 pF.

The experimental circuit parameters were chosen to have the values of \( L_c = 25 \mu \)H, \( C_c = 1000 \) pF and the resulted gain was shown to be with a value of "1.22" which is in close agreement with that theoretically calculated.

b) Load Resistance

The theoretical calculations for the optimum condition of the maximum gain of circuit amplifier using tunnel diode of the type 3N301B shows that, the gain has greater values as the load has the value of 10 k. ohm. The gain is greater than unity, and less than this value, as \( R_L \) less than 10 k. ohm (Fig. 8).
Effect of Shunt Resistor

As pointed by ChirLian [9], a stable amplifier can be obtained if the tunnel diode in the circuit is shunted by a small enough resistance. The magnitude of the appropriate shunt resistance ($r_0$) values are computed to get the maximum gain for the amplifier circuit using tunnel diode of the type 2 301B. The theoretical shunt resistance values adapted to calculations of gain appear to be in general agreement with those realized in practice. Fig. (9) shows the effect of the shunt resistance values on the calculated gain of the circuit amplifier, where resistance values range from 0.10 ohm up to 10 ohm was investigated. It is clear from the figure that as the shunt resistor ($r_0$) be small enough, less than 1 ohm, the gain will be high.
Dependence of gain on Operating Conditions

1- Dependence on Input Frequency

The effect of the operating input frequency (F) on the theoretically calculated gain (A) versus the normalized frequency (N = w / w*) was studied for GaAs tunnel diode amplifier circuit. The study included, as shown in Fig. 10, three values of input frequencies: 10^7, 10^8 and 10^9 Hz, which corresponding to the: medium (short wases), high, and very high frequency ranges respectively. It is clear that, the gain has a nearly constant value which ranges from "1.26" at F: 10^7 Hz to "1.29" at F: 10^9 Hz. On the other hand, the peak points are shown to be shifted toward lower normalized frequency values as the operating input frequency increases. This is so, the shape is function of the dynamic negative resistance (-R_o), the frequency and the resonance nature of the circuit (L_C and C_C). The theoretical calculations of the gain as a function
of the operating frequency are shown to be in good agreement with that results obtained experimentally at the same operating conditions.

![Graph showing gain vs. normalized frequency](image)

**Fig. 10:** The Effect of the Operating Input Frequency \( f \) on the Calculated Gain \( A \) Versus the Normalized Frequency \( n = w/w^* \).

2– Dependence on the Operating Bias Voltage

Variations in operating bias voltage \( U_o \) affect the measured gain of tunnel-diode amplifiers. The \( U_o \) was chosen to be at the middle of the negative dynamic resistance region. The gain is shown to increase linearly with the increase in the applied bias voltage (with a correlation coefficient value of 0.96), as shown in Fig. 11.

Effect of normalized Parameters of Tunnel Diode on the Calculated Gain

The theoretical analysis were extended in order to show the effect of the normalized parameters of the devices on the amplifier in order
Fig. 11: The Effect of the Operating Bias Voltage \( (U_c) \) on the Measured Gain \( (A) \) Using T.D. of the Type Au 301 A.

to obtain the optimum circuit parameters for a peak gain. The normalized parameters are: \( M = r_0 / R_o \) and \( Q = C_D / C_C \).

1- Dependence on the Parameter \( M = r_0 / R_o \)

Figure (12) shows the dependence of the calculated gain on the normalized frequency \( (N = c / w^*) \) for different \( (M) \) values, while the rest parameters are kept constant, for tunnel diode type Au301A. It is clear from the figure that, the calculated gain of the circuit amplifier is a function of the normalized parameter \( (M) \), i.e. on both the shunt resistor \( (r_0) \) and the dynamic negative diode resistance \( (-R_o) \). It increases as \( (M) \) increases, i.e., with decreasing the negative dynamic diode resistance \( (-R_o) \). The calculated gains have their peak values at the same normalized frequency point \( (N = 0.02) \).
Fig. 12: Dependence of the Calculated Gain on the Normalized Frequency \((\nu = w/w^*)\) for Different M Values while the Rest Parameters are Constant.

2- Dependence on the Parameter \(Q = C_D/C_C\)

Figure (13) shows the dependence of the calculated gain on the normalized frequency for different values of \((Q)\), while the rest parameters are kept constant, for the same tunnel diode type. It is clearly seen that, the gain increases with the normalized frequency, reaching a peak point at a certain normalized frequency value, then decreases at higher frequency levels. The peak gain has almost the same value of "1.29" at different values of \((Q)\). On the other hand, it tends to shift towards the higher frequency levels, as the \((Q)\) ratio increase, i.e., as the diode capacitor increases.

From the above results it is clear that, the gain of the tunnel diode circuit is a function of both the negative dynamic diode resistance \((-R_o)\) and the shunt diode capacitor \((C_D)\). The dependence on the diode
capacitor is restricted only on the value of the normalized frequency at the peka gain.

**Phase Angle, ($\varphi$)**

The dependence of the phase angle ($\varphi$) of the amplifier circuit on the normalized input frequency ($N = \omega/\omega^*$) was analyzed using both; GaAs (type Au.301A), and InSb (type YT) tunnel diodes. This relation is shown in Fig. (14) for GaAs devices. It is clear from the figure that, the phase angle ($\varphi$) has periodic dependence on the normalized frequency and it has values between $0^\circ$ and $\pm 90^\circ$ for increasing the normalized frequency. This regular changing apply equally well, with the two diode types.
CONCLUSION

From the study, analysis and experimental, and theoretical results obtained, the following conclusions can be deduced:

— The gain of circuit amplifier exceeds unity.

— The gain increases with the frequency, reaching a peak at certain value of the frequency, then it decreases, at higher frequencies, down to a constant plateau value.

— The peak gain of the tunnel amplifier depends on:
  a) Device physical parameters ($C_D$, $-R_O$ and device material).
  b) Circuit parameters ($L_C$, $C_C$, $R_L$, $r_0$).
  c) Operating conditions ($U_0$, $F_O$).
— The shape of the gain-frequency dependence is a function of the dynamic negative resistance (−R), frequency, and the resonance nature of the circuit (L₀, C₀).

— The amplitude characteristics of the circuit amplifier, measured dynamic negative resistance (−R), frequency, and the resonance at peak frequency, is linear.

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