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Criteria for Plasma Domains in Gunn Diode Fabricated from GaAs and InP

Hayder A. Ahmed
Department of Physics, College of Science, University of Basrah, Basrah-Iraq.
e-mail: dr.hayder73@yahoo.com

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Abstract:

Various parameters are proposed relevant to criteria for physical domains in solid-state plasmas. Strongly-and Weakly-coupled classical plasmas are divided according to the plasma parameter Γ. Classical and quantum domains are separated according to the quantum degeneracy parameter Λ .The weakly-coupled degenerate plasma is described in terms of the quantum compression parameter r_s. In this paper, the application is made to Gunn diode, one of the long lasting Transferred Electron Devices (TED's), fabricated from GaAs and InP, and suggested a new study to analyze the modes of operation of both devices in terms of these parameters by varying the charge-carrier concentration along the device layers (Substrate and active layer region) at 300K. Incorporating novel empirical relations have been done for the first time, for microwave operating frequency, which lead to other new relations for the device length and charge-carrier concentration, in terms of plasma domains. The four principal domains discussed are: strongly – and weakly – coupled classical plasmas, degenerate plasmas and weakly – coupled degenerate plasmas.

Key Words: Semiconductor devices, Microwave operating frequency, Plasma domains.

1. Introduction:

When an electric field in the material reaches a threshold level in some materials (III-V compounds such as GaAs and InP), the mobility of electrons decreases as electric field is increased [1,2], thereby producing negative resistance. A two-terminal device, that was made of such material can produce microwave oscillations, the frequency of which is primarily determined by the characteristics of the specimen of the materials and not by any external circuit. One of the long lasting Transferred Electron Devices (TED's), known as the Gunn diode, is capable of converting direct current (DC) power into radio frequency (RF) power [3,4]. A Gunn diode is essentially just a piece of doped semiconductor with two electrical contacts on opposite ends. It is called a "diode" because it has just two wires and has a non-linear I/V behavior like normal diodes. The major difference between microwave transistors and transferred electron devices is: the transistors operate with "warm" electrons whose energy is not much greater than the thermal energy (0.026 eV at room temperature) of electrons in the semiconductor, whereas TED's operate with "hot" electrons whose energy is very much greater than the thermal energy [5].

There are several possible modes of operation for these devices [4, 6, 7], but each mode depends on the transfer of electrons from a high mobility state to a higher-energy, low mobility state depends on the material parameters and the operating conditions. The aim of this work is to suggest a new study to analyze these modes of operating in terms of plasma domain parameters such as plasma parameter, quantum degeneracy parameter and quantum compression parameter, by varying the charge – carrier concentration along the device layers (for both semiconductors n-type GaAs and InP). Incorporating novel empirical relations for operating frequency in terms of these parameters, one can get other relations for the device length and the charge – carrier concentration. The four principal domains discussed are: strongly-and weakly-coupled classical plasmas, degenerate plasmas and weakly-coupled degenerate plasmas.

2. Theoretical Background:

a. Parameters and Physical Criteria:

The separation between weakly and strongly-coupled classical plasmas is given in terms of the plasma parameter

$$\Gamma^2 = \frac{2\pi n e^6}{(\varepsilon k_B T)^3} \qquad \text{……(1)}$$

Where n: is the charge-carrier concentration.
e: is the electronic charge.
ε: is the dielectric constant.
K_B: is the Boltzmann constant.
T: is the temperature (K).

The criteria involving Γ are given below:
Γ<<1 Weakly-coupled plasma.
Γ ≥ 1 Strongly-coupled plasma . …(2)

Classical and degenerate plasma domains are separated according to the quantum degeneracy parameter Λ:

$$\Lambda^2 = \frac{2\pi\hbar^2}{m^*}\,\frac{n^{2/3}}{k_B T} \qquad \text{…….(3)}$$

Where m* represents the effective mass of electrons or holes. The quantum degeneracy parameter represents the ratio of the thermal deBroglie wave length to the mean interparticle spacing. Related criteria are given below:
Λ ≥ 1 Degenerate plasma.
Λ<<1 Classical plasma. …….(4)

The quantum compression parameter rs represents the ratio between the interparticle spacing and the effective Bohr radius, i.e.:

$$r_s = \frac{r_o}{a_o^*} = \left(\frac{3}{4\pi}\right)^{1/3} \frac{m^* e^2}{\varepsilon\hbar^2 n^{1/3}} \qquad \text{…….(5)}$$

and the condition for this parameter is:

$r_s \le 1$ Weakly-coupled degenerate. ….(6)

The recapitulation for these criteria is given below:

Classical: Λ << 1	Γ<<1	Weakly-coupled
	Γ ≥ 1	Strongly-coupled.
Quantum: Λ ≥ 1	rs ≤ 1	Weakly-coupled degenerate.

Table (1) illustrates the parameter characteristics given in equations (1, 3 and 5). Particular physical properties of these parameters are as follows: The parameter г is the measure of the mean two- particle potential energy to thermal kinetic energy (both are mass-independent) so that г is independent of mass. The parameter Λ on the other hand, is the measure of the thermal deBroglie wavelength (it depends only on dynamics) to mean interparticle deBroglie wavelength (it depends only on dynamics) and to mean interparticle spacing (determined in terms of charge-carrier concentration). Thus both do not contain the coulomb interaction, so that Λ is independent of the dielectric constant ε. Finally, the parameter r_s represents the ratio between two lengths: the Bohr radius and the mean interparticle spacing (both temperature independent) so that r_s is not dependent on temperature.

Table (1): Parameter Characteristics

Parameters	Independent	Dependent
Γ (Plasma)	**m**	$\Gamma^2 \sim n/(\varepsilon T)^3$
Λ (Quantum degeneracy)	**ε**	$\Lambda^2 \sim n^{2/3}/m^*T$
R_s (Quantum compression)	**T**	$r_s \sim m^*/\varepsilon n^{1/3}$

b. Modes of Operation:

The TED, one of the most important microwave devices, has been extensively used in local oscillators and power amplifiers, covering the microwave frequency range from 1 to 100 GHz [2]. The Gunn oscillator will have a frequency inversely proportional to the time required for the domain to

cross the crystal [7,9]. This time is proportional to the length of the crystal and depends to some degree on the applied voltage.Each domain results in a pulse of current at the output, so the Gunn oscillator produces a microwave frequency, which is determined by the physical length of the chip.
Since Gunn first observed microwave oscillation in the n-type GaAs and n-type InP, various modes of operation have been developed, depending on the material parameters and operating condition [4,6]. The formation of a strong space – charge instability depended on these conditions so that the necessary amount of space charge can be built up within the transit time of the electrons.This requirement sets up a criterion for the various modes of operation of uniformly doped bulk diodes.
There are five major factors that affect or determine the modes of operation:
(1) Doping concentration and doping uniformity in the device.
(2) Length of the active region.
(3) Proper cathode contact.
(4) Type of circuit used.
(5) Operating bias voltage.
There are four basic modes of operation of uniformly doped bulk diodes with low resistance contacts [6,7,10]:

(1) Gunn Oscillation Mode:

This mode is defined in the region where

(a) fL ~10^7 cm/sec.

(b) 10^{12} $cm^{-2} \leq nL < 10^{14}$ cm^{-2}

Where f is the operating frequency and L is the length of the active layer region.

(2) Stable Amplification Mode:

This mode is defined in the region where:

(a) fL ~10^7 cm/sec.

(b) 10^{11} $cm^{-2} \leq nL < 10^{12}$ cm^{-2}

(3) Limited Space – Charge Accumulation (LSA) Mode:

This mode is defined in the region where:

(a) fL > $2*10^7$ cm/sec.

(b) $2*10^4 < n/f < 2*10^5$

(4) Bias – Circuit Oscillation Mode:

This mode occurs only when either Gunn or LSA oscillation exists and is usually in the region where the product of frequency time length is too small to appear in the figure (1) which represents the (modes of operation for Gunn diodes) [11]. In the present work, an analysis of the first three modes is carried out.

3. Simulation and Results:

The important conditions, that appear in Fig.(1), for the delimitation of the TED modes of operation are:
(1) The product of frequency multiplied by the device length (i.e.fL).
(2) The product of doping multiplied by length (i.e. nf).
The frequency multiplied by the devices length is equal to the carrier drift velocity. For n-type GaAs and InP, the maximum electron drift velocities are $2.5*10^7$ cm/sec and $2.2*10^7$ cm/sec respectively [9]. Fig.(2) shows the relation between the operating frequency f(GHz) and the length of the active layer region L(μm) for both semiconductors.

The simulation is made to examine the plasma domain parameters (given in equations 1,3 and 5) for the extrinsic n-type GaAs and n-type InP at 300K by varying the charge – carrier concentration form (10^6 –10^{20})cm^{-3}.

The values of characteristic parameters listed in Table (2) indicate the following:
(1) At the lower charge-carrier concentration, the charge-carrier plasmas remain classical and weakly coupled.
(2) At a concentration of 10^{16} cm^{-3} these plasmas grow generate.
(3) At concentration above or equal to 10^{17} cm^{-3} the n-type materials remain degenerate and grow weakly coupled.
The effective masses and dielectric constants for both semiconductors are obtained from Sze [7].
Also, the analysis of the modes of operation for the Gunn diodes is included in the simulation. It is achieved by analyzing the limitation of each mode to suggest a new study connected with plasma domain parameters (charge-carrier plasmas). Table (3) illustrates novel empirical relations and describes the plasma domains in terms of the operating frequency for the (TED's). These relations have been dealt with for the first time. One can use these relations to get others for the device length and charge-carrier concentration, in terms of plasma domains by using the two conditions (pointed above) and the relation between them.
Table (4) gives the conclusion which is obtained from the empirical relations and listed in Table (3). It describes the characteristics of the charge-carrier plasmas for each mode of operation along the range of frequencies.

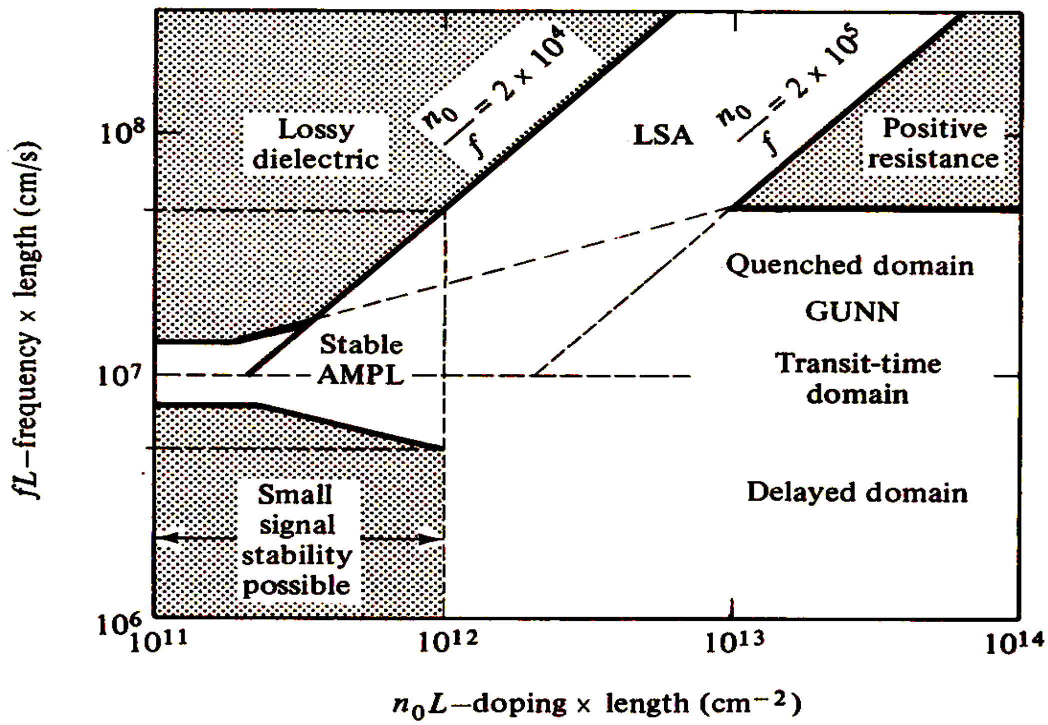
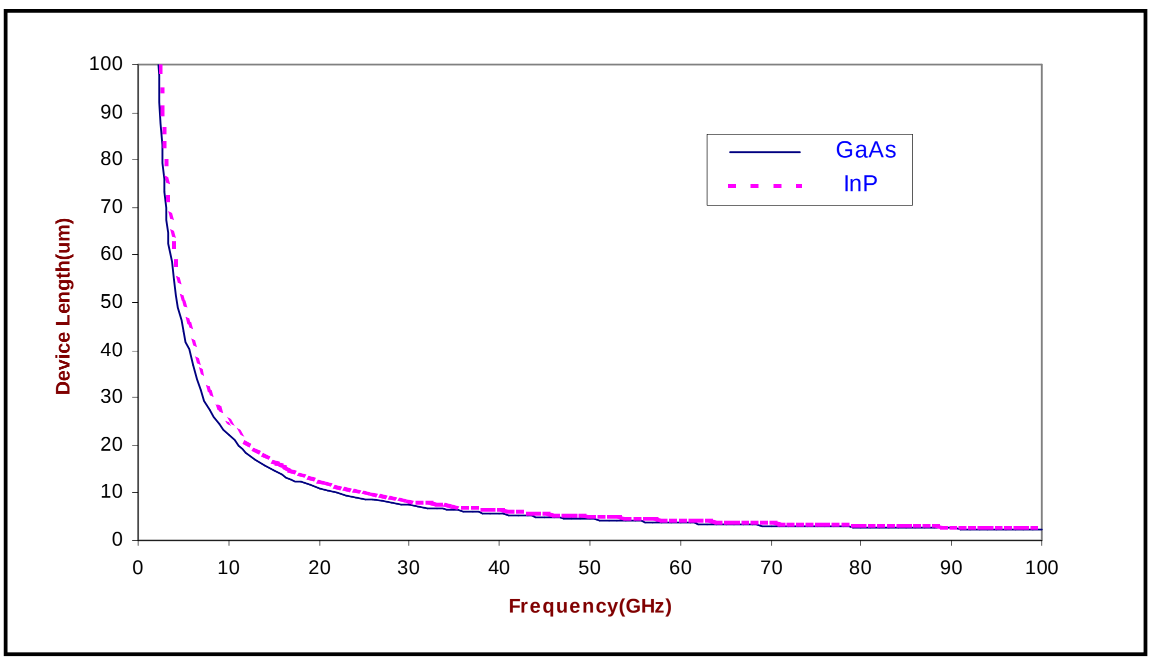


Fig. (1) Modes of operation for Gunn diodes [11]



Fig,(2): Microwave operating Frequency versus the device length

Table (2): Domain parameters in extrinsic n – type GaAs and InP at T = 300K

N (cm^{-3})	n-type GaAs , ε = 13.1 , m_e^* =0.067			n-type InP , ε = 12.4 , m_e^* = 0.077		
	r_s	Γ	Λ	r_s	Γ	Λ
10^{6}	1.66×10^{-4}	9.8×10^{-7}	6033.24	1.546×10^{-4}	1.10×10^{-6}	7376
10^{7}	3.57×10^{-4}	3.1×10^{-6}	2800.38	3.331×10^{-4}	3.48×10^{-6}	3424
10^{8}	7.7×10^{-4}	9.8×10^{-6}	1299.82	7.176×10^{-4}	1.10×10^{-5}	1589
10^{9}	1.66×10^{-3}	3.1×10^{-5}	603.324	1.546×10^{-3}	3.48×10^{-5}	737.6
10^{10}	3.57×10^{-3}	9.8×10^{-5}	280.04	3.331×10^{-3}	1.10×10^{-4}	342.4
10^{11}	7.7×10^{-3}	3.1×10^{-4}	129.98	7.176×10^{-3}	3.48×10^{-4}	158.9
10^{12}	1.66×10^{-2}	9.8×10^{-4}	60.33	1.546×10^{-2}	1.10×10^{-3}	73.76
10^{13}	3.57×10^{-2}	3.1×10^{-3}	28	3.331×10^{-2}	3.48×10^{-3}	34.24
10^{14}	7.7×10^{-2}	9.8×10^{-3}	13	7.176×10^{-2}	1.10×10^{-2}	15.89
10^{15}	0.166	3.1×10^{-2}	6.03	0.1546	3.48×10^{-2}	7.376
10^{16}	0.357	9.8×10^{-2}	2.8	0.3331	0.110	3.424
10^{17}	0.770	0.31	1.3	0.7176	0.348	1.589
10^{18}	1.66	0.98	0.6	1.546	1.100	0.7376
10^{19}	3.57	3.10	0.28	3.331	3.480	0.3424
10^{20}	7.70	9.80	0.13	7.176	11	0.1589

Table (3): Novel empirical relations that describe the relation between the plasma domain parameters and microwave operating frequency for (TED's) modes

Modes	Plasma Domain Parameters	n-type InP		n-type GaAs	
		Lower limit	Upper limit	Lower limit	Upper limit
Gunn Oscillation	Γ	$0.0066\ f^{1/2}$	$0.0611\ f^{1/2}$	$0.007\ f^{1/2}$	$0.0696\ f^{1/2}$
	Λ	$0.592\ f^{1/3}$	$0.2748\ f^{1/3}$	$0.0529\ f^{1/3}$	$0.2454\ f^{1/3}$
	r_s	$16.905\ f^{-1/3}$	$3.6422\ f^{-1/3}$	$21.567\ f^{-1/3}$	$4.6465\ f^{-1/3}$
Stable Amplification	Γ	$0.0021\ f^{1/2}$	$0.0066\ f^{1/2}$	$0.0022\ f^{1/2}$	$0.007\ f^{1/2}$
	Λ	$0.275\ f^{1/3}$	$0.0592\ f^{1/3}$	$0.0245 f^{1/3}$	$0.0529\ f^{1/3}$
	r_s	$36.422\ f^{-1/3}$	$16.905\ f^{-1/3}$	$45.465\ f^{-1/3}$	$21.567\ f^{-1/3}$
LSA	Γ	$0.0042\ f^{1/2}$	$0.0132\ f^{1/2}$	$0.0044\ f^{1/2}$	$0.0139\ f^{1/2}$
	Λ	$0.0436\ f^{1/3}$	$0.094\ f^{1/3}$	$0.039\ f^{1/3}$	$0.0839 f^{1/3}$
	r_s	$22.944\ f^{-1/3}$	$10.65\ f^{-1/3}$	$29.271\ f^{-1/3}$	$13.586\ f^{-1/3}$

Table (4): The conclusion for simulation results listed in Table (3)

Modes	Charge – Carrier Plasmas in both n-type GaAs and InP	
	Lower limit	Upper limit
Gunn Oscillation	Classical and weakly coupled (1-100GHz)	# Classical and weakly coupled (1-8GHz). # Grow degenerate (9-20GHz). # Weakly coupled degenerate (21-100GHz).
Stable Amplification	Remain in the weakly-coupled, Classical domain (1-100GHz)	
LSA	Classical and weakly coupled (1-100GHz)	# Classical and weakly coupled (1-50GHz). # Grow degenerate (51-100GHz).

4. Discussion:

Any advanced semiconductor device requires bulk material of substrates and epitaxial for the high quality active region. Both must be doped to the correct carrier type and impurity level. For (TED's) the n-type doping for the highly – conductive substrate, is from 10^{18} to 10^{19} cm^{-3} and the impurity doping level for the active layer region requirements is from 10^{14} to 10^{16} cm^{-3} [4]. Therefore, according to Table (2), it can be found that: for the active region, with doping concentration from 10^{14} to 10^{15} cm^{-3}, the charge– carrier plasmas remain classical and weakly – coupled. If the active layer has about 10^{16} cm^{-3} doping concentration then the charge – carrier plasmas, in the region, grow degenerate. For the substrate that has a doping concentration equal to or above 10^{17} cm^{-3}, the plasma domains (charge – carrier plasmas) remain degenerate and grow weakly coupled.Table (3) includes novel empirical relations which relate the charge – carrier plasmas to the microwave operating frequency measured in GHz for TED's. These empirical relations are obtained by analyzing the lower and upper limitation for each mode. By using the two conditions (i.e. nL and fL appear, along the x and y – axes respectively, Fig.(1)) and the empirical relations listed in Table (3), other relations can be obtained for device length and doping concentrations in terms of charge – carrier plasmas. For each mode of operation, it can be seen that the plasma parameter Γ and the quantum degeneracy parameter Λ are both proportional to the operating frequency but the quantum compression parameter rs is inversely proportional to the operating frequency.

Table (4) gives the conclusion of the charge – carrier plasmas behavior for each mode of operation, obtained from the empirical relations listed in Table (3).

5. Conclusion:

Extrinsic properties of n-type GaAs and n-type InP at varying charge – carrier concentrations (from 10^{6} to 10^{20} cm^{-3}) at 300K have been examined. Values of characteristic parameters listed in Table (2) indicate the following:

Doping Concentration (cm^{-3})	**10^{6} - 10^{15}**	**10^{16}**	**10^{17} – 10^{20}**
Charge-Carrier Plasmas	**Weakly-coupled, Classical Domain**	**Grow Degenerate**	**Remain Degenerate and Weakly-coupled**

Table (3) gives novel empirical relations for both semiconductors: GaAs and InP. These empirical relations connect the microwave operating frequency and the charge – carrier plasmas (plasma domain parameters). The conclusions of these equations are listed in Table (4). Using the relations given in Table (3), we obtained other relations for device length and doping concentrations in terms of the charge – carrier plasmas. For each mode of operation, the plasma parameter Γ and the quantum degeneracy parameter Λ both proportional to the operating frequency but the quantum compression parameter rs is inversely proportional to the operating frequency.

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معيار مجالات البلازما في ثنائي "Gunn" المصنوع من الكاليوم – آرسنايد و الأنديوم– فوسفات

حيدر عبدالرحيم أحمد
قسم الفيزياء، كلية العلوم، جامعة البصرة، البصرة - العراق.
البريد الألكتروني: ***dr.hayder73@yahoo.com***

خلاصة:

أقترحت معاملات مختلفة ذات صلة في معيارالمجالات الفيزيائية لبلازما الحالة الصلبة حيث ان الأقتران الشديد والضعيف للبلازما الكلاسيكيه يكون مقسماً وفقاً لمعامل البلازما Γ ، أما المجالات الكلاسيكية والكمية تكون مفصولة وفقا لمعامل الأنحلال الكمي Λ وان r_s يمثل معامل الضغط الكمي ويقوم بوصف البلازما المنحلة ذات الأقتران الضعيف. تم في هذا البحث دراسة التطبيقات على ثنائي "Gunn"، وهو احد نبائط الألكترون المنتقل TED ، المصنوع من الكاليوم –آرسنايد و الأنديوم–فوسفات. وكذلك تم اقتراح طريقة تحليل جديدة لأنماط تشغيل هذه النبائط بدلالة المعاملات اعلاه وبواسطة تغيير تركيز حاملات الشحنات على طول طبقات هذه النبائط (منطقة طبقة القاعدة ومنطقة الطبقة الفعالة النشطة) عند درجة حرارة 300K . تم الحصول على علاقات تجريبية تصف تشغيل/عمل الترددات المايكروويفية داخل هذه النبائط والتي قادت بدورها الى الحصول على علاقات جديدة اخرى تصف طول النبيطة وكذلك علاقات تركيز حاملات الشحنات بدلالة مجالات البلازما. المجالات الأربعة الرئيسية التي تمت مناقشتها هي: البلازما الكلاسيكية ذات الأقتران الشديد، البلازما الكلاسيكية ذات الأقتران الضعيف، البلازما المنحلة و البلازما المنحلة ذات الأقتران الضعيف.