Study of IMPATT Diodes

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Introduction

An IMPATT diode (impact ionization avalanche transit-time diode) is a form of high-power semiconductor diode used in high-frequency microwave electronics devices. They employ both impact ionization and transit-time properties of semiconductor structures to produce negative dynamic resistance at microwave frequencies. The negative resistance comes from the time domain in which the AC current and voltage are out of phase. There are two delays that will cause the current to lag the voltage. First one is the avalanche delay caused by the finite buildup time of the avalanche current, and second one is the transit-time delay for the carriers to cross the drift region. When these two delays add up to half-cycle period, the diode dynamic resistance is negative at the corresponding frequency.

According to the cause of the negative dynamic resistance, an IMPATT diode need to have an avalanche region and a drift region. The basic members of the IMPATT diode family are shown in Fig 1. These are the Read diode, the one-sided abrupt p-n junction, the p-i-n diode (Misawa diode), the two-sided (double-drift) diode, the hi-lo and lo-hi-lo diodes (modified Read diodes).

The first IMPATT oscillation was obtained from a simple silicon p-n junction diode biased into a reverse avalanche break down and mounted in a microwave cavity. Because of the strong dependence of the ionization coefficient on the electric field, most of the electron–hole pairs are generated in the high field region. The generated electron immediately moves into the N region, while the generated holes drift across the P region. The time required for the hole to reach the contact constitutes the transit time delay.

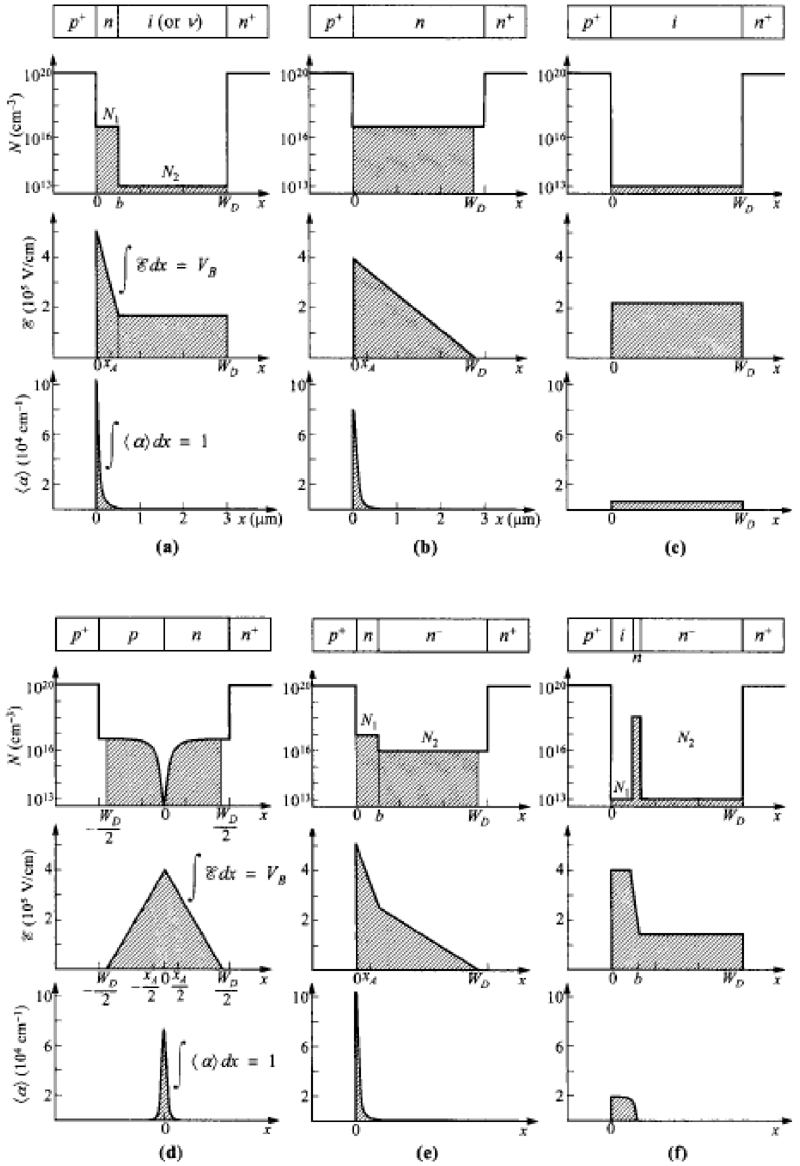


Fig 1 Doping profile, electric-field distribution, and ionization integrand for (a) Read diode; (b) one-sided abrupt diode; (c) *p-i-n* diode; (d) double-drift diode; (e) *hi-lo* structure; and (f) *lo-hi-lo* structure.

The IMPATT diode is now one of the most powerful solid-state sources of microwave frequency. They can be used as oscillators to generate microwaves as well as amplifiers. The main advantage of the IMPATT diodes is their high-power capability. These diodes are used in a variety of applications from low-power radar systems to proximity alarms. A major drawback of using IMPATT diodes is the high level of phase noise they generate.

Operational Principle

If a free electron with a sufficient energy strikes a silicon atom, it will break the covalent bond of silicon and liberate a pair of electron and hole from the covalent bond. And if the electron liberated gains energy by being in an ultrahigh electric field and liberates other electrons from other covalent bonds, then this process can cascade very quickly into a chain reaction, which will produce a large number of electrons and a large current flow. This phenomenon is called the impact avalanche.

When a p-n junction is reverse biased, and at breakdown, the n-region is punched through and forms the avalanche region of the diode. The high resistivity region is the drift zone through which the avalanche generated electrons move toward the anode.

We consider first the injection phase delay and transit-time effect of an idealized device whose structure is shown in Fig 2 where we move the x-origin to the right of the avalanche region (plane of charge injection). The terminal voltage and the avalanche generation rate are also shown in relation to each other. The terminal voltage, of angular frequency ω, has a mean value at the verge of avalanche breakdown V_B. In the positive cycle, avalanche multiplication begins. The generation rate of carriers, however, as shown, is not in unison with the voltage or field. This is because the generation rate is not only a function of the field but also of the number of existing carriers. After the field passes the peak value, the generation rate continues to grow until the field is below the critical value. This phase lag is approximately π and is called the injection phase delay.

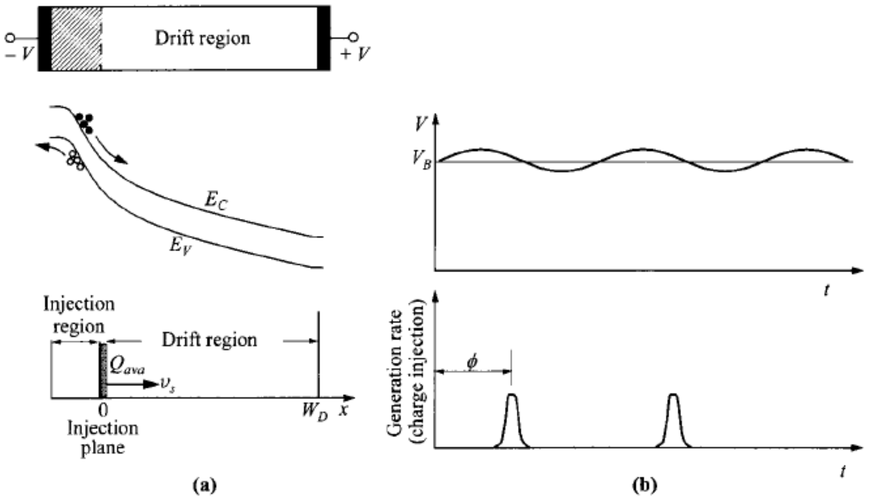


Fig 2 (a) Idealized IMPATT diode with carrier injection at x = 0 and a drift region with saturation velocity. (b) Terminal voltage and avalanche generation rate in time domain. The avalanche lags the voltage by $\phi \approx \pi$.

Assume that an avalanche charge pulse is injected at x = 0, in Fig 2, with a given phase angle delay ϕ with respect to the terminal voltage. Also assume that the applied DC voltage across the diode causes the carriers to travel at the saturation velocity v_s, in the drift region, $0 \leq x \leq W_D$. After some calculation, we can obtain the impedance of the device

$$R_{ac} = \frac{cos\phi - cos(\phi + \theta)}{\omega C_D \theta}$$

$$X = -\frac{1}{\omega C_D} + \frac{sin(\phi + \theta) - sin\phi}{\omega C_D}$$

We consider next the influence of the injection phase ϕ on the AC resistance

R_{ac}. When ϕ equals zero (no phase delay), the resistance is proportional to $(1 - cos\theta)/\theta$, which is always greater or equal to zero, as shown in Fig 3a; that is, there is no negative resistance. Therefore, the transit-time effect alone cannot give rise to negative resistance. However, for any nonzero ϕ, the resistance is negative for certain transit angles. For example, at $\phi = \pi/2$, the largest negative resistance occurs near $\theta = 3\pi/2$, as shown in Fig 3b. For $\phi = \pi$, the same occurs near $\theta = \pi$, as shown in Fig 3c. This corresponds to the IMPATT operation, in which the buildup of the injection current due to impact avalanche introduces a phase delay of about π, and the transit time in the drift region gives an additional π delay.

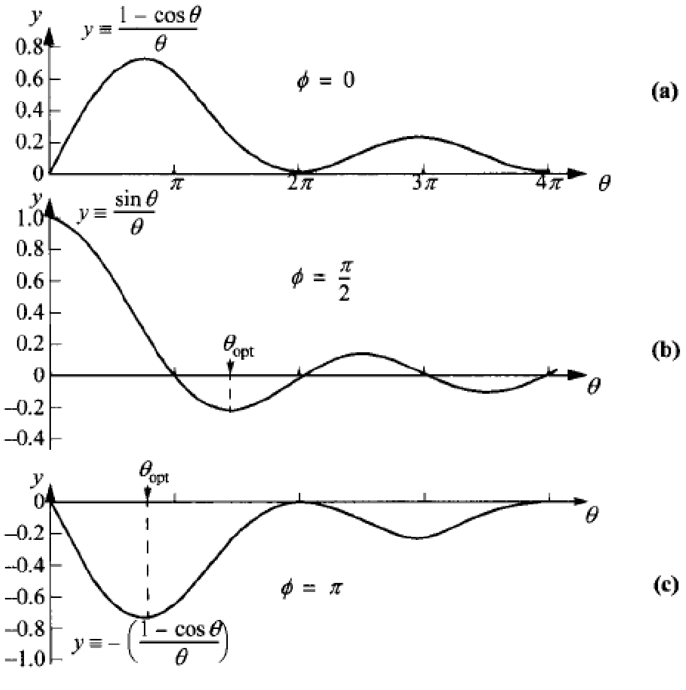


Fig 3 AC resistance vs. transit angle for three different injection phase delays. (a) $\phi = 0$. (b) $\phi = \pi/2$. (c) $\phi = \pi$.

The foregoing considerations have confirmed the importance of the injection delay. The problem of finding active transit-time devices has been reduced to finding a means to delay the injection of conduction current into the drift region. From Fig 3, we observe that the sum of the injection phase and the optimum transit angle, $\phi + \theta_{opt}$, is approximately equal to 2π. As ϕ increases from zero, the magnitude of the negative resistance becomes larger.

Recent Work on IMPATT

Impact Avalanche Transit Time (IMPATT) devices are premier solid-state devices for generating sufficiently high RF power with high DC to RF conversion efficiency at millimeter-wave (mm-wave) and terahertz (THz) frequencies. There will give two topics of recent research in IMPATT. First one is the new structure proposed that would give high efficiency, high microwave power and low noise. And second one is the new models to that applying external magnetic field in tuning the properties of the IMPATT devices.

Heterojunction IMPATT Diodes

With the advancement of technology, heterojunction IMPATT diodes have been conceptualized by researchers for localizing the avalanche zone using lattice-matched semiconductors, one with a higher ionization rate for the high-field avalanche region and the other with a lower ionization rate for the low-field drift region. During the last decade, several theoretical and experimental reports on the potentiality of hetero-junction IMPATT diodes, both double drift region (DDR) and double avalanche region (DAR), have found place in the published literature. In this section, a new combination of materials, GaAs and $\mathrm{Ga_{0.52}In_{0.48}P}$ to build the heterojunction will be given. In this work, the GaAs layer has higher ionization rate for the avalanche region, while the ternary material $\mathrm{Ga_{0.52}In_{0.48}P}$ with lower ionization rate is designed as the drift region. The result of simulation indicates that with a proper choice of the ternary layer width for the drift region not only the microwave properties but also the noise behavior of the diode can be improved.

The one-dimensional schematic diagram of the proposed device structure is shown in Fig 4. It is a symmetrical DDR structure with doping distribution of the form $\mathrm{n^+nnppp^+}$.

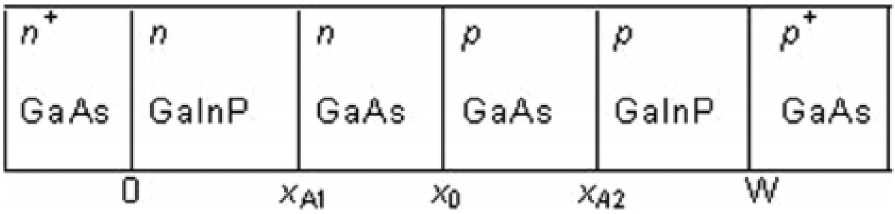
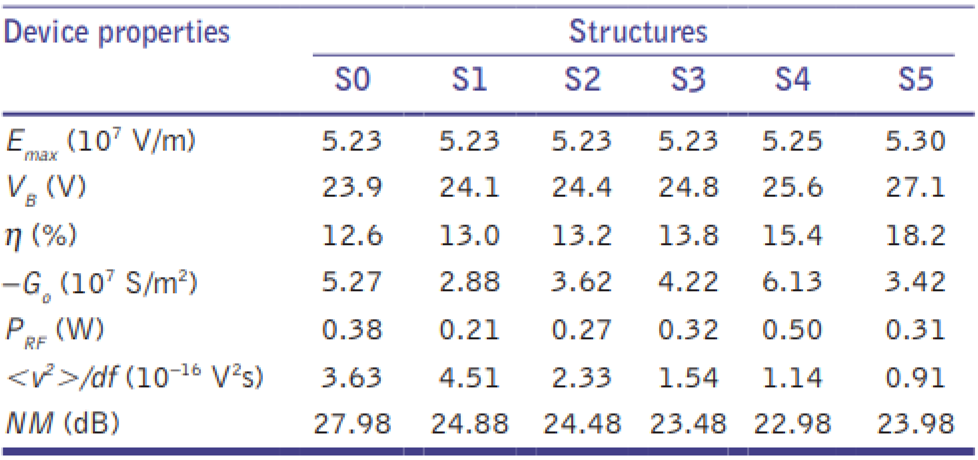


Fig 4 1-D schematic diagram of the proposed heterojunction DDR IMPATT diode. (active region = 0 to W, avalanche region = x_{A1} to x_{A2}, junction = x_0, drift regions = 0 to x_{A1} and x_{A2} to W)

The $\mathrm{n^+}$ and $\mathrm{p^+}$ regions, which are used for ohmic electrical contacts to external circuit, are the highly doped regions that cause the electric field to drop to zero suddenly and thus they contribute negligible value to the active width of the diode. The doping concentration for each $\mathrm{n^+}$ and $\mathrm{p^+}$ region is taken as $1.0 \times 10^{26}\ m^{-3}$. The total depletion region width for all the diode structures are considered to be 800 nm, with the n– and p-regions consisting of 400 nm each. Different ternary layer width of $\mathrm{Ga_{0.52}In_{0.48}P}$ layer will be chosen as 100 nm, 200 nm, 300 nm, 400 nm and 500 nm, respectively. For all the heterojunction diode structures, the doping concentration for each n and p region are taken to be $1.1 \times 10^{23}\ m^{-3}$. The results obtained from the simulation of all the IMPATT diode structures with different ternary layer width are summarized and presented in Table 1.



Device properties	Structures					
	S0	S1	S2	S3	S4	S5
E_{max} (10^7 V/m)	5.23	5.23	5.23	5.23	5.25	5.30
V_B (V)	23.9	24.1	24.4	24.8	25.6	27.1
η (%)	12.6	13.0	13.2	13.8	15.4	18.2
$-G_o$ (10^7 S/m^2)	5.27	2.88	3.62	4.22	6.13	3.42
P_{RF} (W)	0.38	0.21	0.27	0.32	0.50	0.31
$<v^2>/df$ (10^{-16} V^{2}s)	3.63	4.51	2.33	1.54	1.14	0.91
NM (dB)	27.98	24.88	24.48	23.48	22.98	23.98

Table 1 Microwave and noise properties of the GaAs homojunction and GaAs/GaInP hetero-junction IMPATT diode structures at the design frequency of 140 GHz. (The structure S0 is a GaAs homojunction IMPATT diode. S1, S2, S3, S4 and S5 are GaAs~$\mathrm{Ga_{0.52}In_{0.48}P}$ hetero-junction IMPATT diode structures with a total ternary layer width of 100 nm, 200 nm, 300 nm, 400 nm and 500 nm, respectively.)

It is observed from Table 1 that as the increase of the ternary layer width in the drift region, the breakdown voltage V_B as well as the efficiency η of the diode increases while the maximum electric field remains nearly same for all the structures. Moreover, the noise performance shows that the introduction of $\mathrm{Ga_{0.52}In_{0.48}P}$ will lead to less noise to the system.

In general, the introduction of a suitable choice of $\mathrm{Ga_{0.52}In_{0.48}P}$ layer width, the device efficiency, breakdown voltage and the microwave power become remarkably high compared with those of its GaAs homo-structure counterpart. Further, the hetero-structure IMPATTs in general are found to be less noisy as compared with the pure homo-structure diode.

Effect of magnetic field on the RF performance of IMPATT

There are many ways to control the properties of the IMPATT, beside the traditional electronic and optical tuning mechanisms, another method is also possible for externally controlling the IMPATT properties, that is magnetic field tuning. The application of magnetic field in properly biased IMPATT diode causes a number of effects in its microscopic operation such as changes of the carrier motion, the carrier distributions and the electrostatic potential distribution. This work presented a two-dimensional (2-D) large-signal model to study the effect of steady magnetic field on the RF performance of millimeter-wave double-drift region IMPATT devices. And results show that the frequency tuning of the source of around 3.64 GHz is achievable with maximum sensitivity of about $-1.59\mathrm{GHzT}^{-1}$ for the application of transverse magnetic field varying from 4.0 to 5.0 T

The 3-D model of the aforementioned device structure is shown in Fig 5.

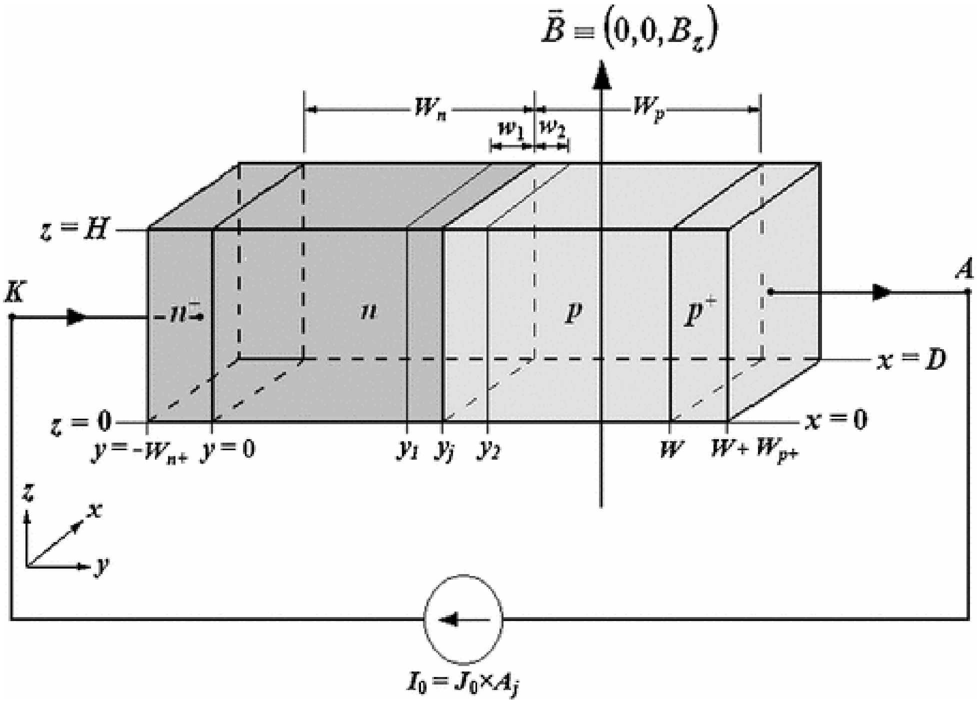


Fig 5 3-D model of the n^+npp^+ structured DDR IMPATT diode ($w_1 = w_2 = 0.1\mu m$)

After the simulation and measurement, the result shows that with different magnetic field applied to the system, the properties of the device will change.

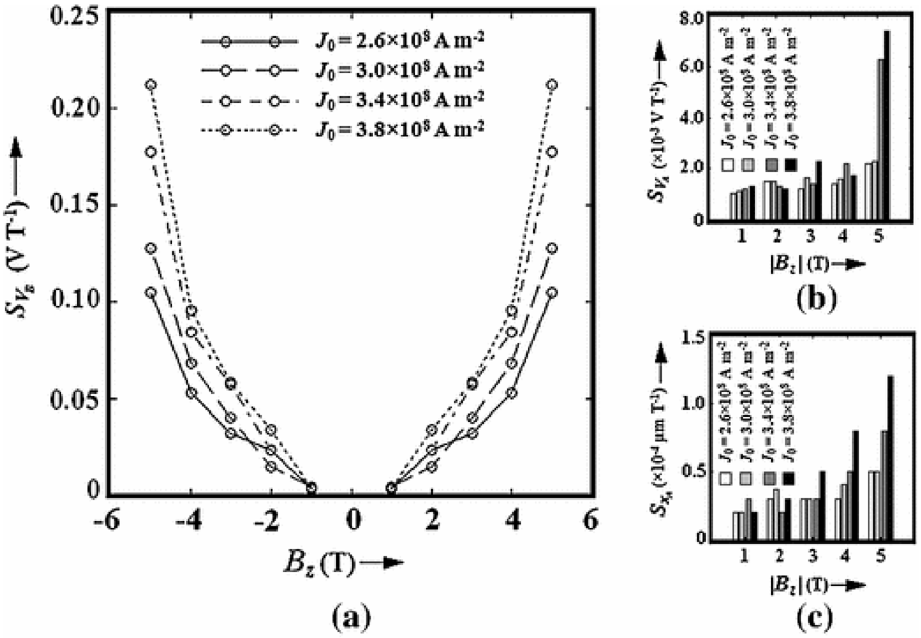


Fig 6 Graphs showing the sensitivities of (a) breakdown voltage, (b) avalanche region voltage drop and (c) avalanche region width with respect to the applied magnetic field for different bias current densities.

Fig 6 shows that with the increase of external magnetic field, the sensitivity of the breakdown voltage V_B, the avalanche voltage drop and the avalanche region width increase as well, especially for field larger than 4.0T.

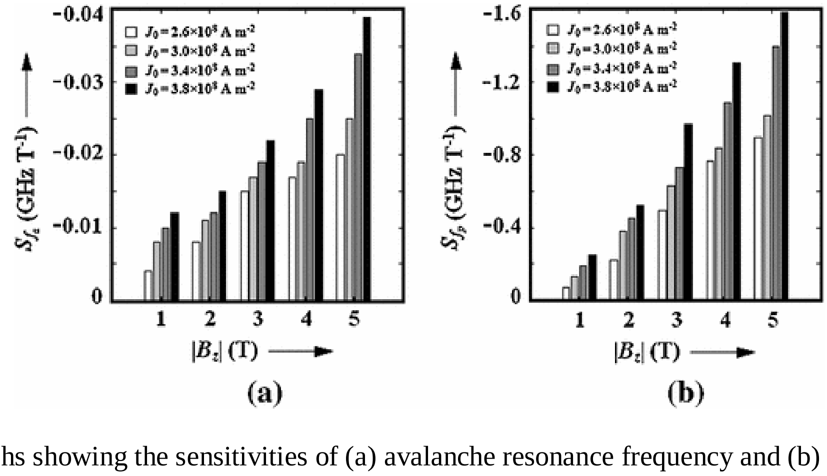


Fig 7 Bar graphs showing the sensitivities of (a) avalanche resonance frequency and (b) optimum

frequency with respect to the applied magnetic field for different bias current densities.

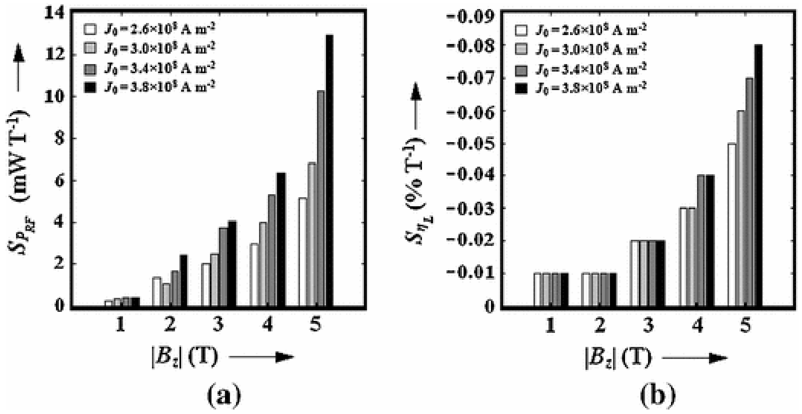


Fig 8 Bar graphs showing the sensitivities of (a) RF power output and (b) DC to RF conversion efficiency with respect to the applied magnetic field for different bias current densities.

From Fig 7 and Fig 8, it is observed that the frequency and power tuning of the source of around 3.64GHz and 26mW are achievable with maximum sensitivities of about -1.59GHzT^{-1} and 12.95mWT^{-1} respectively for the application of transverse magnetic field varying from 4.0 to 5.0T.

The arrangement proposed in this paper may be named as magnetic field tunable avalanche transit time (MAGTATT) device. It has immense potential be used in various areas of communication systems such as phased array antennas for space communication, active phased array Radar systems, etc.

References

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