Varactor Structure, Idea of Operation, Characteristics And Application

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***Abstract*—Varactor is P-N junction whose principle of operation depending on variable junction capacitance of P-N junction by applying reverse bias voltage. it has many types depending on doping profile, semiconductor used in it's manufacturing. this diode is used in many application such as tuning circuit for high frequency signals. this paper will explain it's structure ,basic idea of operation , characteristics , practical applications and limitation for it's usage.**

***Index Terms*—Varactor , Junction Capacitance , Tuning circuits**

I. Introduction

In recent years semiconductor p-n junctions have found wide use in parametric amplifiers, harmonic generators, and frequency modulators. These applications result from the fact that the space charge region of the junction is voltage dependent and thus easily variable which made it easy to exploit in application requiring changing width of space charge region. Another semiconductor p-n junctions which in some instances shows a greater dependence of capacity upon voltage is called varactor a shortened form of variable reactor, referring to the voltage-variable capacitance of a reverse-biased p-n junction. In this paper , the structure, idea of operation, characteristics, practical application and some limitation will be explained in details.

II. Preliminaries

A. Gauss' Law [1]

There is relation between electric field and charge density. the law which describe this relation is called Gauss' Law. Flux line which is a measure of the strength of a field passing through a surface is defined such that $\psi = Q_{en}$ (where Q_{en} is total charge enclosed in surface). it was found that

$$Q_{en} = \int_S D.ds \tag{1}$$

(where D is electric flux density on Gaussian surface and ds is differential surface element in Gaussian surface). it was also found that

$$D = \epsilon\varepsilon \tag{2}$$

(where ε is electric field and ϵ is relative permitivity of medium) divergence theorem was build on Gauss's law prior which lead to equation:

$$DivD = \rho_v \tag{3}$$

according to relation between electric flux density and electric field explained above divergence theorem will be given as the follows:

$$\frac{d\varepsilon(x)}{dx} = \frac{\rho(x)_v}{\epsilon} \tag{4}$$

B. Capacitance Law

A capacitor is a device used to store charge.capacitor can store charges depending on two major factors—the voltage applied and the capacitor's physical characteristics, such as its dimensions, dielectric material. The capacitance C is the amount of charge stored per volt and generally it is given by the following formula:

$$C = \left|\frac{dQ}{dV}\right| \tag{5}$$

for parallel plate capacitor, $Q = \rho_s A$ and $V = \frac{\rho_s d}{\epsilon}$. so, according to previous equation:

$$C = \left|\frac{dQ}{dV}\right| \tag{6}$$

$$= \frac{\rho_s A}{\frac{\rho_s d}{\epsilon}} \tag{7}$$

$$= \frac{\epsilon A}{d} \tag{8}$$

(where d is very small compared to Area of the plates so that the plates can be considered infinite plate with surface charge density ρ_S).

III. Structure

Certain specifications for a varactor diode should be followed during manufacturing it, so that diode operation is optimized around the reverse bias junction capacitance, and not just be a conventional diode. The diode is manufactured with a large area and a specific doping profiles which will be explored when showcasing varactor characteristics [2].

The p-type and n-type layers of the varactor are either silicon or gallium arsenide depending on the application. For lower frequency applications, silicon is used, and for higher frequency applications gallium arsenide is preferred.

By introducing another lightly doped n-type layer called the cathode layer (typically 1 to 10 thousand times less doped) between the p and n type material, and having the main p and n region doping heavily doped, we can get different characteristics in a varactor. Note that the heavily doped n-type layer is called the substrate, and the p-type layer has a small thickness. For this reason, varactors will be classified into two types: Abrupt and hyper abrupt varactors, depending on the doping profile. It is also possible to create a linearly graded doping profile varactor, but its practical applications are limited compared to the previously mentioned types.

After the diode is formed, the rest of the device is manufactured for use. The n material is put on a mesa structure connected to a molybdenum stud which will act as cathode for the whole device. This specific design decreases the parasitic resistance of the device. The p material is connected to a gold wire which is connected to another molybdenum stud which will act as anode. The whole thing is then enclosed in a ceramic layer [3].

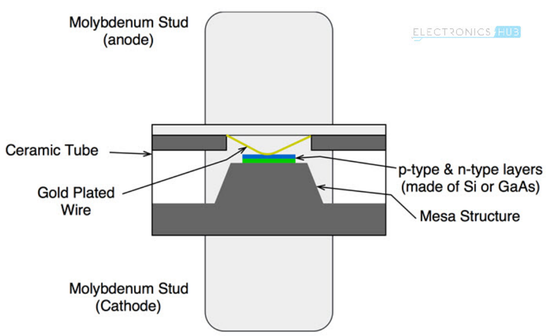

Fig. 1: Varactor Diode Construction Structure.

IV. Basic Idea of Operation

A qualitative description of the basic principles of the varactor is helpful in understanding the more detailed theory. Let us consider separate regions of p-type and n-type semiconductor material, brought together to form a junction as shown in (Fig. 2), Before they are joined, the n material has a large concentration of electrons and few holes, whereas the p material has a large concentration of holes and few electrons. Thus holes diffuse from the p side into the n side, and electrons diffuse from n to p [4].

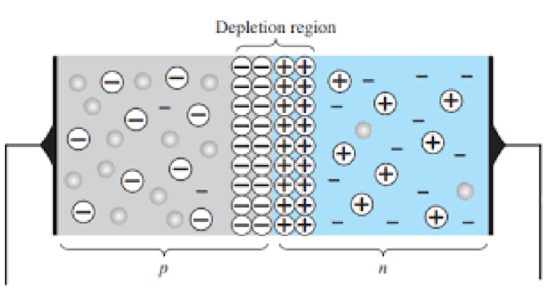

Fig. 2: p-n junction

As electrons diffuse from the n region, positively charged donor atoms are left behind (N_d^+). Similarly, as holes diffuse from the p region, they uncover negatively charged acceptor atoms (N_a^-).
The net positive and negative charges in the n and p regions induce an electric field in the region near the junction, in the direction from the positive to the negative charge, or from the n to the p region.
The net positively and negatively charged regions are referred to as the space charge region (also called depletion region) (Fig. 3).

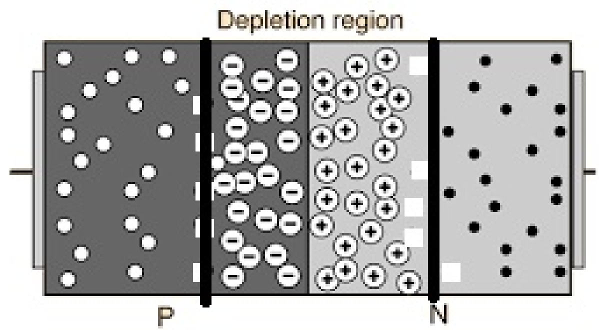

Fig. 3: Depletion region in a p-n junction

This leads to the capacitive behavior of the P-n junction as we will discuss shortly . There are basically two types of capacitance associated with a junction:
1. The junction capacitance due to the dipole (the uncompensated donor ions (N_d^+) and the uncompensated acceptors (N_a^-)) in the transition region.
2. The charge storage capacitance arising from the lagging behind of voltage as current changes, due to charge storage effects in the neutral region outside the depletion region.
The junction capacitance is dominant under reverse-bias conditions, whereas the charge storage capacitance is dominant when the junction is forward biased.
As we discussed above, since we are dealing with varactors (voltage-variable capacitance of a reverse-biased p-n junction) we will focus our attention on the junction capacitance.
The capacitance of the resulting dipole is slightly more difficult to calculate than is the usual parallel plate capacitance, but we can obtain it in a few steps, starting by using the general definition of the capacitance [5]:

$$C = \left|\frac{dQ}{dV}\right| \tag{9}$$

Since the width of the depletion region at equilibrium is:

$$W = \sqrt{\frac{2\epsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)} \tag{10}$$

But we dealing with the non-equilibrium case with voltage V applied on the p-n junction.
So the proper expression for the width of the depletion region

is:

$$W = \sqrt{\frac{2\epsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)} \tag{11}$$

where V can be either negative (reverse bias) or positive (forward bias) .
Since the uncompensated charge Q on each side of the junction varies with the depletion region width, so variations in the applied voltage result in corresponding variations in the width as shown by (Fig. 4), which cause variation in the charge, as required for a Capacitor. The value of Q can be written in

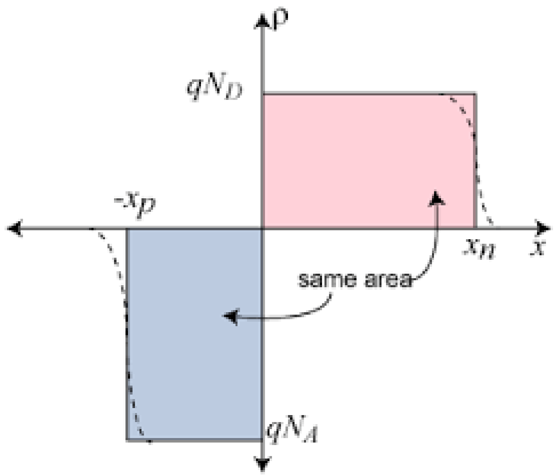

Fig. 4: The concentration of the uncompensated charges

terms of doping concentration and the depletion region width on each side of the junction :

$$|Q| = qAx_{n0}N_d = qAx_{p0}N_a \tag{12}$$

We can relate the total width of the depletion region W to the individual widths x_{n0} and x_{p0} by using the following equations :

$$x_{p0} = \frac{N_d}{N_a + N_d}W \tag{13}$$

$$x_{n0} = \frac{N_a}{N_a + N_d}W \tag{14}$$

Thus the charge on each side of the dipole is:

$$|Q| = qA\frac{N_d N_a}{N_a + N_d}W = A\sqrt{2\epsilon q(V_0 - V)\frac{N_d N_a}{N_a + N_d}} \tag{15}$$

By substituting in the capacitance general equation we get that:

$$C_j = \left|\frac{dQ}{d(V_0 - V)}\right| = \frac{A}{2}\sqrt{\left[\frac{2q\epsilon}{(V_0 - V)}\frac{N_d N_a}{N_a + N_d}\right]} \tag{16}$$

Where the quantity C_j is a varactor (voltage-variable) capacitance.
It is noteworthy, that the form of the parallel plate capacitor formula is obtained from the expressions for C_j and W :

$$C_j = \epsilon A\sqrt{\left[\frac{q}{2\epsilon(V_0 - V)}\frac{N_d N_a}{N_a + N_d}\right]} = \frac{\epsilon A}{W} \tag{17}$$

V. Characteristics

Theorem 1 :
Capacitance of a varactor Depends on doping profile
It can be shown that the varactor capacitance is a function of doping profile. First, the difference between abrupt and hyperabrupt junction varactors is explained: In an abrupt

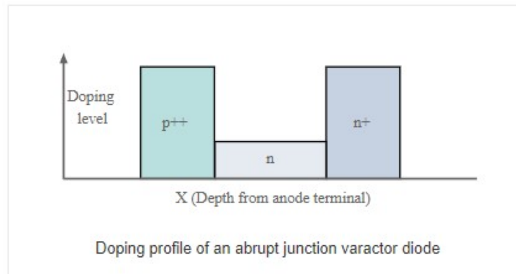

Fig. 5: Abrupt Doping Profile.

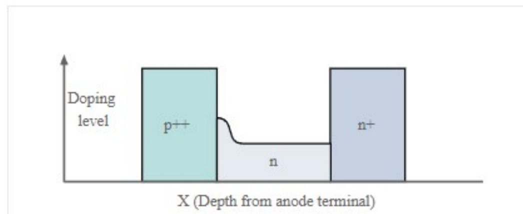

Fig. 6: Hyperabrupt Doping Profile.

junction diode, the doping concentration of the cathode layer with respect to distance from the pn junction is relatively constant. The following shows how the capacitance varies with voltage in case of abrupt varactor and hyperabrupt varactor.
These graphs both follow the following equation:

$$C_j = \frac{C_{j0}}{\left(\frac{V_0 - V_r}{V_0}\right)^{\gamma}} \tag{18}$$

Where C_{j0} is the junction capacitance at zero bias, V_r is the reverse bias voltage, V_0 is the diode potential barrier, also can be denoted as ϕ, and γ is a constant that varies depending on the doping profile. Its values vary between $0.5 \leq \gamma \leq 2$, where the abrupt junction type has a value γ = 0.5, while the hyperabrupt has a value of γ.
This is a more general equation to find C_j compared to the first equation, which can be considered a special case of this equation when $\gamma = 0.5$.
In a hyperabrupt junction, the carrier concentration in the cathode layer is reduced exponentially as the distance from the junction increases. This will cause the capacitance to be much more sensitive to voltage changes and give larger capacitance values.
Theroem 2 :
Equivalent circuit of varactor and Quality Factor (Q)
Varactor diodes can be modelled as follows:
Where R_p is the resistance of the p-layer, R_{n+} is the resistance of the substrate layer, C_j is the equivalent capacitor of the varactor and Rn is the cathode layer resistance.

Fig. 7: Varactor Equivalent Circuit.

Note that R_n is denoted as a variable resistance, because the resistivity of this layer depends on the depletion layer width. It is known that the width varies with the bias voltage, therefore the resistance will also vary with bias voltage, where it will be maximum at zero bias (when W is minimum) and will continue to decrease as VR increases (as long as it does not exceed breakdown voltage).
It is concluded that R_n is a function in VR.
The total equivalent impedance of the device will be calculated as such:

$$Z_t(V_r) = R_p + R_{n^+} + R_n(V_r) - jX_{cj}(V_r) \tag{19}$$
$$= R_t(V_r) - jX_{cj}(V_r) \tag{20}$$

Quality factor of varactors
The quality factor can be defined as a way to determine how well a device will perform.
The quality factor will be shown to be inversely proportional to frequency, so typically there is a specific maximum frequency rating for each varactor.
The quality factor for any device can be obtained by dividing the energy stored by the energy dissipated in the circuit, which will be as follows in case of varactors:

$$Q = \frac{Energy_{stored}}{Energy_{dissipated}} = \frac{Im(Z_t(V_r))}{Re(Z_t(V_r))} \tag{21}$$
$$= \frac{X_{cj}(V_r)}{R_t(V_r)} = \frac{1}{\omega C_j(V_r) R_t(V_r)} \tag{22}$$

Where ω is $2\pi f$, f is the frequency of operation, X_{cj} is the reactance due to the junction capacitance, and R_t is the total series resistance due to each region of the varactor. C_j and R_t are both functions in VR.
The minimum acceptable level of Q depends on the application. In voltage controlled oscillators, it must not drop below 10.
In tunable filters, it must not drop below 100. The frequency must be considered to provide acceptable performance.
It is conventional that varactor manufacturers specify a Q measured at 50MHz at an arbitrary bias voltage. This can be used to obtain Q at different frequencies for the same bias voltage just by equating ratios such as the following:

$$Q(f) = Q_{specified}\frac{f_{specified}}{f} \tag{23}$$

Practically, it was shown that that as frequency increases, the actual measured Q for a varactor diode is lower than the value predicted by the previous equation. This is because not only does the frequency dependent component of the diode impedance increase as frequency increases, the resistance caused by skin effect also increases. This equation does not account for the increase in ohmic resistance as well.
It is also important to note that in practice, Q will be even lower than in theory because RT will be higher in a completed varactor die. This is because the elements added also add resistances in series, such as the ceramic cover, the molybdenum studs, the structure on which the cathode is situated and the wires.These are called parasitic resistances. This is why the studs are gold-plated and gold wires are used instead of copper because it conducts electricity better. The structure is manufactured as in a table like- mesa structure. All of this keeps the parasitic resistances to a minimum.

VI. Capacitance variations with voltage in different types of Junction [4]

In the abrupt p-n junction, the capacitance varies as the square root of the reverse bias V_r as seen by equation (8). In a graded junction, however, the capacitance can usually be written in the form

$$C_j \quad \alpha \quad {V_r}^{-n} \quad for \quad V_r >> V_0 \tag{24}$$

For example, in a linearly graded junction the exponent n is $\frac{1}{3}$. Thus the voltage sensitivity of C_j is greater for an abrupt junction than for a linearly graded junction.
For this reason, varactor diodes are often made by epitaxial growth techniques, or by ion implantation.

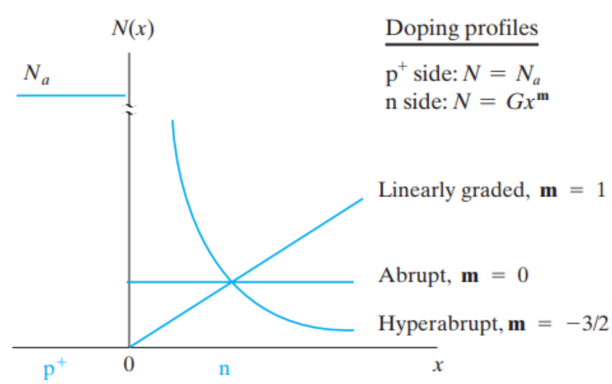

Fig. 8: Graded junction profiles: linearly graded, abrupt, hyper abrupt.

The epitaxial layer and the substrate doping profile can be designed to obtain junctions for which the exponent n in Eq.(23) is greater than $\frac{1}{2}$. Such junctions are called hyper abrupt junctions.
In the set of doping profiles shown in (Fig. 8), the junction is assumed p_+-n so that the depletion layer width W extends primarily into the n side.
Three types of doping profiles on the n side are illustrated, with the donor distribution $N_d(x)$ given by Gx^m, where G is a constant and the exponent m is 0, 1, or $\frac{-3}{2}$.
It can be shown that the exponent n in Eq. (23) is $\frac{1}{(m+2)}$ for

the p_+-n junction.
Thus for the profiles of (Fig. 8) , n is $\frac{1}{2}$ for the abrupt junction and $\frac{1}{3}$ for the linearly graded junction.
The hyper abrupt junction with $m = \frac{-3}{2}$ is particularly interesting for certain varactor applications, since for this case $n = 2$ and the capacitance is proportional to ${V_r}^{-2}$.
When such a capacitor is used with an inductor L in a resonant circuit, the resonant frequency varies linearly with the voltage applied to the varactor.

VII. Applications

Phase-locked loop [6]: Varactors are used in the manufacture of resonators, Resonators are circuits that are designed to oscillate at a certain frequency.
They are used in frequency mixers and multipliers (also called harmonic multipliers), function generators or detectors. Varactors are also used in manufacture of variable frequency oscillators, which is an integral building block of many circuits, such as the phase-locked loop.
An important use for phase locked loops is making FM demodulators and frequency synthesizers.
Filters: An obvious way to use varactors is tune receiving-end filters, where an analog control is used to increase or decrease voltage across varactor to change its capacitance and changing the resonance frequency as series RLC circuit acts as band-pass filter that allow resonance frequency to pass and block the other frequencies.
Tunable filters are important in communication systems to separate channels.
Most tunable filters consist of multiple band pass filters put together and are made more for a single specific application rather than multiple usages.
Using a varactor in a tunable filter makes it so easy for the tunable filters to be condensed into just one filter circuit.
Ultimately, this can save on parts, size, and most importantly, cost since varactor manufacturing can be cheaper than current multi-filter designs.
The varactors are tuned with a DC bias and then able to tune within the certain frequency range of that filter.
The tunability of the varactor filters has also proven to be efficient.These filters can be made to manufacture antennas for example.
Audio modulation/output: Varactors can be placed across a generator of an audio signal, such that the voltage will vary up and down in line with the audio waves according to the capacitance changes.
VCO: VCO's (voltage-controlled oscillators) are another very important component used in communication systems. The device before introducing varactors can already tune into difference frequencies based on its voltage, but using a varactor in the circuit design will enhance its tunability even further.
Audio modulation/output: VCOs can be placed across a generator of an audio signal, such that the voltage will vary up and down in line with the audio waves according to the capacitance changes.
The devices which do this are called "Frequency and Phase Modulators"

VIII. Numerical Evaluation

Theorem 1 :
Taking log in both sides before graphing will make it a simpler process to draw. It is important to note that in a hyper abrupt junction, γ will also be a function in V_r, therefore the $log(C) - log(V_r + V_0)$ graph for the hyper abrupt junction will not be linear. The function by which γ changes with respect to VR depends on the doping profile of the material.

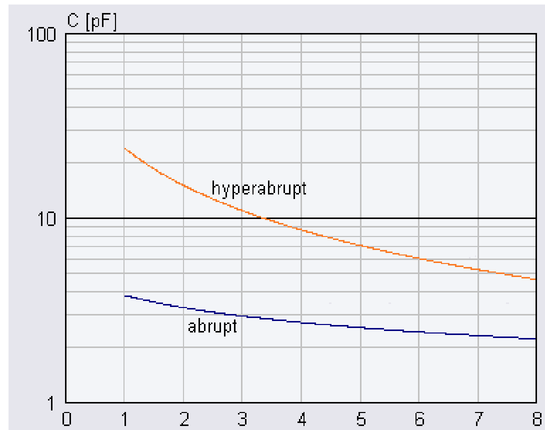

Fig. 9: $C - V$ characteristics without taking log with both types on same graph to show in C values for the same reverse bias voltage.

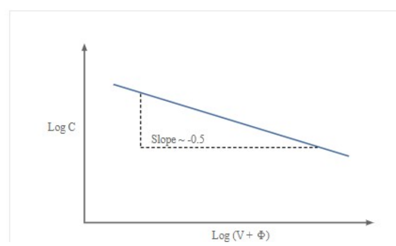

Fig. 10: Log C - log V curve of abrupt varactor.

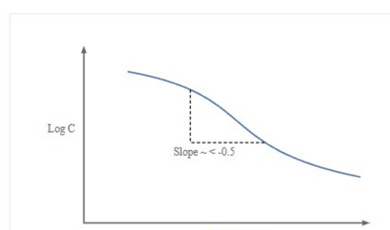

Fig. 11: log C - log V curve of hyper abrupt varactor.

It is shown that the capacitance of hyper abrupt junction varactors is higher than that of abrupt junction varactors for the same reverse bias voltage, as was suggested by the characteristics. The next two figures also showcases how the slope exponent γ changes non linearly in case of the hyper abrupt junction. However, the voltage-capacitance curve of the hyper-abrupt varactor can be approximated very accurately in a piecewise manner. This approach offers a better capacitance-voltage fit but it will require more work by the designer. The equation will be as follows:

$$C_j = \frac{C_{j0}}{\left(\frac{V_0 - V_r}{V_0}\right)^M} \tag{25}$$

Using this approach, the values of Cj, Vr, V0 and M (which is another way to denote γ) are selected to produce curves that coincide with a portion of the real C-V hyperabrupt graph. When enough points are drawn to cover most of the real graph, fitting is carried out.

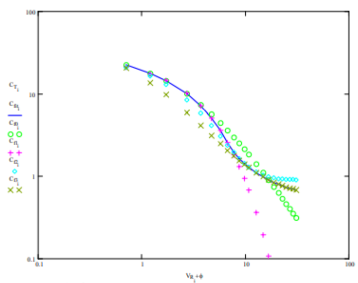

Fig. 12: Picture of each individual graph (dotted) on top of the real C-V graph (solid)

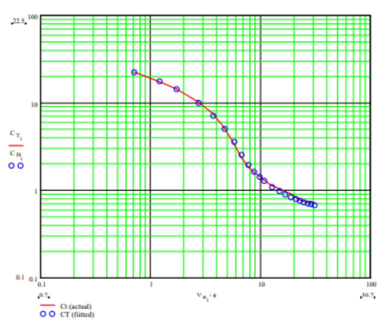

Fig. 13: The graphs after fitting on top of the real C-V graph

Theorem 2 :

From the graph shown in fig.14, it is clear that the quality factor Q decreases dramatically as the frequency increases. Most varactors have capacitance values in picofarads, therefor according to the quality factor equation, it will be high up to a few GHz, before it would drop to a low or unacceptable value.

It should be noted that the hyper abrupt capacitor experiences this drop earlier than normal abrupt capacitors.

IX. Limitations

At large signal amplitudes, it can introduce distortions as the capacitance would be affected by change of signal voltage, which causes inter-modulation. Requires relatively large reverse voltage for operation as the capacitance is variable with respect to the square root of the voltage. Their operation

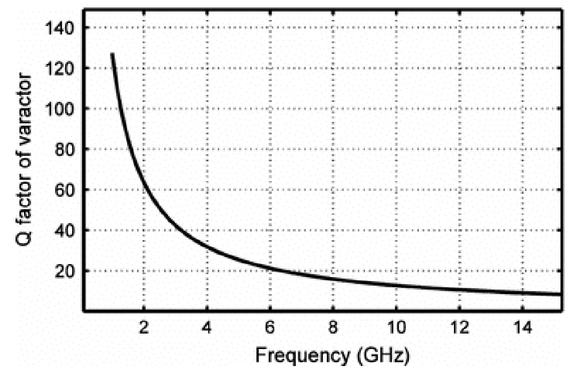

Fig. 14: Simulated Q Factor of Varactor Vs Frequency at turning voltage of 0.2 V.

is dependent on using them in backward bias, making them useless when used in forward bias.

X. Conclusion

This paper showcased the basics of varactors, its types and what factors does this type classification depends on, Possible structures and which structure is better in various applications, operation idea: how varactor works and on what factors does it's operation depends.

It also showed the results of simulations to clarify the characteristics.

Practical applications were also briefly discussed for the varactor and few of many ways it can be used. limitations in using varactor and how to use it properly.

Only pn-varactors (varicaps) were studied in this paper, which is considered the most basic type of varactors.

Despite this, they have a broad range of applications, and they continue to improve and new types are manufactured, like MOS varactors or thin film BST varactors, which offer the same usability but with greater efficiency and speeds.

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