HYPERABRUPT TUNING DIODE THEORY AND APPLICATION TO AM RADIO

By Peter M. Norris and Paul Heidenreich
Motorola Semiconductor Products INC.
Phoenix, Arizona

Summary

Tuning diodes are voltage-variable capacitors (varactors) based on semiconductor junction phenomena, which can be used for electric tuning applications. This paper is intended to explain how varactors function, introduce a new varactor applicable to AM radio, and describe the characteristics of this device.

Introduction

It is felt that these varactors will become important circuit components because electronic tuning offers many advantages over mechanical tuning. Electrically and electronically tuned circuits are small, reliable and extremely fast acting. However, electric tuning in the AM band has not been extensively applied because the tuning ratios of the available tuning elements were low. This situation has changed with the introduction of the Epicap tuning diode series where tuning ratios exceed 20:1.

Generally for electric tuning it is desirable to vary capacitance or inductance as a function of voltage or current. The rate of change of capacity with voltage is, of course, of fundamental importance. For hyperabrupt semiconductor junctions the best devices approach a capacity varying inversely with the square of applied voltage. This is discussed further in the section on tuning diode characteristics.

Tuning Diode Characteristics

Tuning diodes are voltage-variable capacitors based on PN junction theory. Conventionally speaking, when we refer to a semiconductor diode we normally visualize a 2-terminal p-n junction operated in the forward conduction region (as a rectifier) or in the reverse avalanche region (as a zener diode). From this standpoint, the word diode applied to an Epicap* is actually a misnomer - for while the Epicap is indeed a 2-terminal PN junction, it operates neither as a rectifier, nor as an avalanche device. Rather, it operates principally in the region between forward conduction and reverse breakdown - the very region in which a conventional diode is considered to be cut off. In this operating region the PN junction can be represented by the circuit of Fig. 1.

The capacitor C_C and inductors L_S and L_{SX} are parasitic elements. C_C is the package capacitance and is quite small, usually less than a picofarad. The package lead inductance L_S is internal inductance and can be neglected at low frequencies being usually less than 5nH. If the external lead inductance L_{SX} is also neglected the equivalent circuit reduces to that shown in FIG. 2.

*T M Motorola

The capacitance C_J, knows as junction capacitance, is inherently associated with all PN junctions and, while it represents an undesirable parasitic in conventional diode operation, it is the specific mechanism that permits the device to function as a voltage-variable capacitor. This is true because the capacitance value, as will be seen later, actually varies as a function of applied voltage. This factor cannot only be used for electric tuning but also for harmonic generation and parametric amplification.

The cause and behavior of the junction capacitance can be determined from basic semiconductor theory, as follows:

When a junction is formed between n-type and p-type material, there is a cross-migration of charges across the junction. Electrons from the n-region cross the junction to neutralize positive carriers near the junction in the p-region, and "holes" from the p-region cross the junction to neutralize the "excess" electrons near the junction in the n-region. As a result of this migration, all free charged particles are swept out of the immediate vicinity of the junction area. And, in the process, a contact potential or space charge (about 0.6 volts for silicon) appears across the junction, Figure 3a.

This structure acts very much like a slightly charged capacitor, with the depletion layer representing the dielectric and the semiconductor material adjacent to the depletion layer representing the two conductive plates.

If an external voltage is connected across the PN junction so as to reinforce the contact potential (reverse bias), the depletion layer increases, resulting in a capacitance decrease, Figure 3b. If a forward voltage is applied, the depletion layer decreases, Figure 3c. However, if the external forward voltage is made large enough to overcome the contact potential, forward conduction occurs and the capacitance effect is destroyed.

It is obvious, therefore, that the value of the junction capacitance is a function of the externally applied voltage, so long as the junction itself remains reverse biased. The relationship is:

$$C = \frac{C_o}{(1 + V/\phi)^{\gamma}} \qquad (1)$$

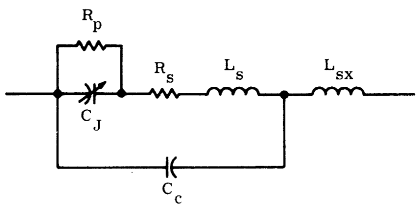

Figure 1—Equivalent Circuit of an Epicap.

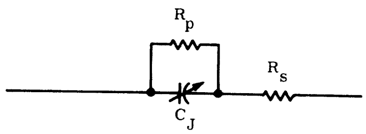

Figure 2—Low Frequency Equivalent Circuit.

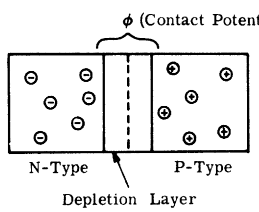

Figure 3a—A Representative P-N Junction.

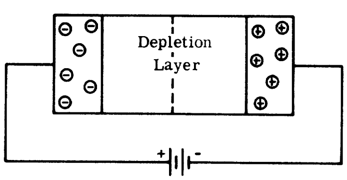

Figure 3b—Reverse Voltage Forces.

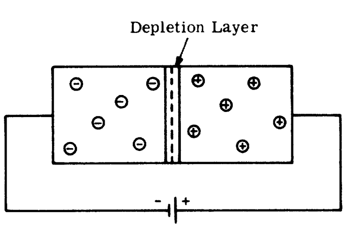

Figure 3c—Forward Voltage Forces.

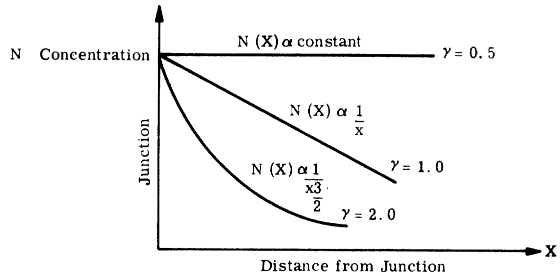

Figure 4—Impurity Concentration Profile.

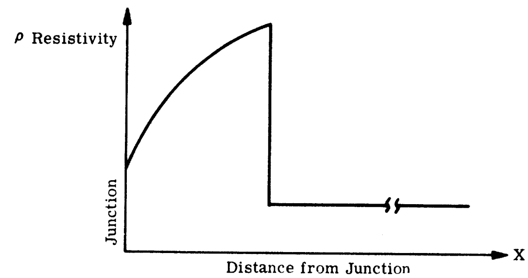

Figure 5—Resistivity Profile for Retrograded Junction.

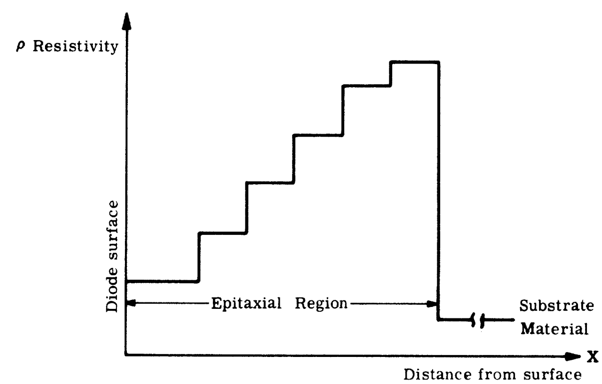

Figure 6—Stepwise Approximation of Resistivity Profile.

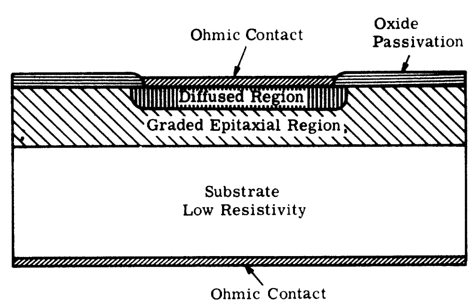

Figure 7—Cross Section of Tuning Diode Die.

where:

C = capacitance at voltage V
C_o = capacitance at zero bias
V = voltage across the diode (reverse bias)
ϕ = contact potential
γ = power law of the junction, determined impurity gradient

The exponent is a function of the impurity gradient of the PN junction. It may vary from approximately 1/3 for graded junctions to about 1/2 for step junctions, and to 2 or greater for hyperabrupt junctions.

The quality factor Q is a function of both the series and parallel resistances.

For a capacitor with series resistance:

$$Q_s = \frac{1}{\omega C R_s} \qquad (2)$$

where:

Q is the quality factor
ω is the frequency in radians/sec.
C is the capacitance in farads
R_s is the series resistance in ohms

When the resistance is in parallel with the capacitance

$$Q_p = \omega C R_p \qquad (3)$$

where:

R_p is the parallel resistance.

If both series and parallel resistances are present the following is a simple formula for Q:

$$\frac{1}{Q} = \frac{1}{Q_s} + \frac{1}{Q_p} \qquad (4)$$

where Q_s and Q_p are calculated by equations 1 and 2 respectively, and $Q_p \gg 1$.

It should be emphasized that Q is a function of junction capacitance and therefore bias.

For most applications the temperature stability of all the capacitor parameters are important. Epicap stability is not expected to equal the stability of the best air capacitors, but a high level of parameter stability has to be maintained either by the device itself or with some sort of compensating mechanism.

Returning to Equation (1)

$$C = \frac{C_o}{(1 + V/\phi)^{\gamma}} \qquad (1)$$

The contact potential, ϕ, varies with temperature decreasing as temperature increases at a rate of 1.5 to 2.0 mV/C^o. The change in capacitance is therefore minimized for large reverse bias, V.

AM Tuning Diode Requirements

Table model and portable radios operating from 535 to 1610 KHz require a total capacitance change in excess of 9:1 to cover the band. The RF section of a typical mechanical tuning capacitor may vary capacitance by a factor in excess of 12:1 in order to overcome the effect of stray and circuit capacitance. Typical capacitors have minimums of 10-20 pF with maximums in the 200-400 pF range. The loop antennas normally used have unloaded Q's typically in excess of 200. The mechanical capacitor Q is high enough to prevent degradation of the unloaded circuit Q significantly.

The remaining characteristic is the exponent γ defined in Equation 1. It is shown elsewhere[1] that γ equal to 2 is most desirable as the distortion products are minimized. Tuning voltage and frequency are linearly related and, therefore, antenna-local oscillator tracking is easily accomplished.

To summarize, the desirable electrical specifications for a device to tune the broadcast band are:

$\gamma = 2$
C_{min} = 10-20 pF
$C_{max}/C_{min} \geqq 20$

In addition, the Q should be as high as possible. Reverse leakage should be as low as possible. Furthermore, it would be desirable to have breakdown voltage as high as possible. Unfortunately, these requirements are not unrelated and, as is usually the case, to optimize one restricts another. These considerations are discussed in the next section.

The variation in depetion layer width or spread determines the junction diode's capacitance change. In turn, depletion layer spread variation is dependent on impurity profile or distribution in these regions. Assuming depletion layer spread in one direction away from the junction and treating the depletion layer as a parallel plate capacitor with charges separated a distance X in a dielectric ϵ,

$$C = \frac{\epsilon}{X} \text{ farads/cm}^2 \qquad (5)$$

Also, the junction capacitance expressed as a function of externally applied voltage as shown previously,

$$C = \frac{C_o}{(1 + \frac{V}{\phi})^{\gamma}} = \frac{\phi^{\gamma} C_o}{(\phi + V)^{\gamma}} \qquad (1)$$

Ignoring the effects of contact potential, , and simplifying equation (1)

$$C = \frac{K_1}{V^{\gamma}} \qquad (6)$$

Substituting equation (5)

$$\frac{\epsilon}{X} = \frac{K_1}{V^{\gamma}} \qquad (7)$$

The applied voltage V is related to charge density by Poission's equation:

$$\nabla^2 V = \frac{-\rho}{\epsilon}, \qquad (8)$$

or in one dimension,

$$\frac{d^2V}{dX^2} = \frac{-\rho\ (X)}{\epsilon}, \qquad (9)$$

where:

$$\rho(X) = qN(X),$$

and N(X) represents impurity or doping concentration[2].
Therefore:

$$\frac{d^2V}{dX^2} = \frac{-qN(X)}{\epsilon},$$

and from equation (7):

$$V = \frac{K_1 X^{1/X}}{\epsilon}, \qquad (10)$$

and: $$\frac{d^2V}{dX^2} = \frac{K_1}{G}\ \frac{1}{\gamma}\left(\frac{1}{\gamma} - 1\right) X^{(1/\gamma - 2)} = \frac{-qN(X)}{\epsilon}, \qquad \textbf{(11)}$$

or, $$N(X) = K_2 \frac{1}{\gamma}\left(\frac{1}{\gamma} - 1\right) X^{\left(\frac{1}{\gamma} - 2\right)} \qquad \textbf{(12)}$$

Equation (12) dictates the impurity profile into which the depletion layer must spread.

Note that it was assumed in the development shown in Figure 4, that all depletion layer spread was in one direction from the junction. This assumption is quite valid since $N_A >> N_D$ for the diffused junctions that are used to fabricate hyperabrupt junction tuning diodes. Where N_A and N_D denote acceptor and donor impurity concentrations at the junction.

As shown in Figure 4, the impurity concentration profile dictates the capacitance versus voltage characteristic of the diode. Actual device capacity and voltage breakdown depend upon the level at which the impurity variation of equation (12) occurs.

To determine these levels let:

X_m = max
V_B = Voltage breakdown

Substituting

$$V_B = \frac{K_1 X_m^{\frac{1}{\gamma}}}{\epsilon} \qquad (13)$$

$$N_{(X_m)} = K_2 \frac{1}{\gamma}\left(1 - \frac{1}{\gamma}\right) X_m^{\left(\frac{1}{\gamma} - 2\right)} \qquad (14)$$

$$\left(\frac{C}{A}\right)_{min} = \frac{K_3}{X_m} \qquad (15)$$

Equations 12, 13, 14 and 15 are the primary design equations. Once the required voltage breakdown or maximum working voltage is specified, capacitance, maximum depletion layer thickness and impurity profile across the depletion layer spread region can easily be determined.

To optimize Q as defined in (4), R_s must be minimized and R_p maximized. R_p, the junction shunt resistance, is generally neglected since good diode fabrication techniques will keep R_p high. R_s is defined as

$$R_s = \frac{\rho(X)\ L}{A}$$

where $\rho(X)$ is resitivity of the silicon in regions outside the depletion layer. To keep R_s low, the range over which ρ is high is limited to the maximum depletion layer width X_m. The remaining structure of the device is very low resistivity, therefore minimizing R_s, see Figure 5.

To fabricate Hyper Epicaps which exhibit $\gamma \approx 2$ with high Q, retrograded Epitaxial techniques have been employed. The required resistivity profile has been carefully stepwise approximated, Figure 6.

Low resistivity substrate material is used to reduce R_s. Additional epitaxial material is grown at the surface to allow for a step junction diffusion without significantly effecting predetermined impurity doping. A surface passivated structure has been employed to minimize parasitic effects such as R_p which would degrade both diode Q and reverse leakage current. In addition, this technique will offer highly ohmic contact to both anode and cathode regions.

Some typical resuls are:

BV = 14.5 volts at I_R = 10 A
I_R = 5nA at V_R = 10 volts
Q = 378 at f = 1mc, V = 2 volts
C_2 = 210.4 pF
C_5 = 80.5 pF
C_{10} = 15.4 pF

Conclusion

In order to evaluate performance of the hyperabrupt junction tuning diodes, a pair of devices, similar to those described in the text, and matched to within 2% at 2.0, 5.0, and 10 volts of bias for (ϕ+ V) vs. capacitance, were used to replace a 2- Section ganged, mechanical variable capacitor in a line-operated, transistorized AM radio.

Before and after conversion, the receiver was tested in accordance with IEEE Standard #186, "Methods of Testing Amplitude-Modulation Broadcast Receivers" to provide a comparison between diode and mechanical variable performance. No attempt was made to modify the antenna and oscillator tank transformers.

Although some degradation in $\frac{S + N}{N}$, and selectivity were noted with the tuning diodes, the performance was considered satisfactory. Performance could be improved by re-designing the oscillator-tank and antenna circuits thus making it possible to design practical, quality, solid-state electric tuning for AM converters with the new hyperabrupt junction tuning diodes.

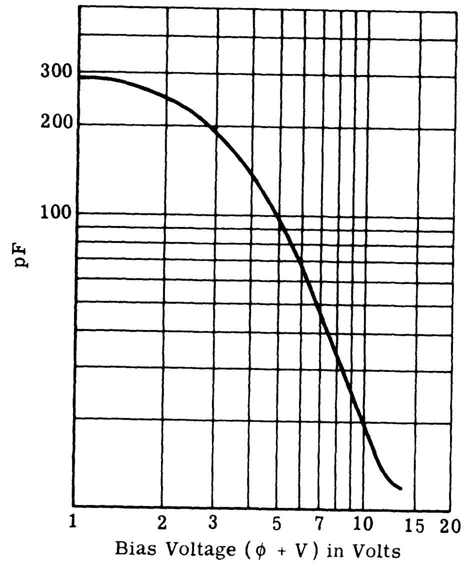

Figure 8—Capacitance Vs. (∅ + V) for Hyperabrupt Junction Tuning Diode.

REFERENCES

1. De Cola, Ray, "Varactor Tuning Applied to AM/FM Receivers." (To be presented at 1967 Chicago Spring Conference on Broadcast and Television Receivers.)

2. Phillips, Alvin B., "Transistor Engineering," McGraw-Hill 1962, p 217.