AN-551
Application Note

TUNING DIODE DESIGN TECHNIQUES

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Epicap tuning diodes offer many advantages over air variable capacitors. However in some applications their capacitance drift with temperature changes must be overcome with suitable compensation techniques. This note discusses a number of considerations to be employed in designs using tuning diodes.

MOTOROLA Semiconductor Products Inc.

TUNING DIODE DESIGN TECHNIQUES

INTRODUCTION

Voltage variable capacitors or tuning diodes are best described as diode capacitors employing the junction capacitance of a reverse biased PN junction. There is a wide range of available capacitances and different device types. The capacitance of these devices varies inversely with the applied reverse bias voltage.

Tuning diodes or Motorola's "Epicaps*" have several advantages over the more common variable capacitor. They are much smaller in size and lend themselves to circuit board mounting. They are available in most of the same capacitance values as air variable capacitors. Tuning diodes offer the designer the unique feature of remote tuning.

Epicaps, as opposed to earlier versions of voltage variable capacitors exhibit many new improvements. Lower leakage, significantly higher Q and uniformity are just some of these advantages. However, the capacitance of all tuning diodes inherently varies with temperature and may require compensation. A simple scheme is available for compensation of the temperature drift, resulting in stabilities as good as, or better than, that of air capacitors. This note contains the details for compensating Motorola's Epicap diodes.

SIMPLIFIED THEORY

A tuning diode is a silicon diode with very uniform and stable capacitance versus voltage characteristics when operated in its reverse biased condition. In accordance with semiconductor theory, a depletion region is set up around the PN junction. The depletion layer is devoid of mobile carriers. The width of this depletion region is dependent upon doping parameters and the applied voltage. Figure 1A shows a PN junction with reverse bias applied, while Figure 1B shows the analogy, a parallel plate capacitor. The equation for the capacitance of a parallel plate capacitor given below predicts the capacitance of a tuning diode.

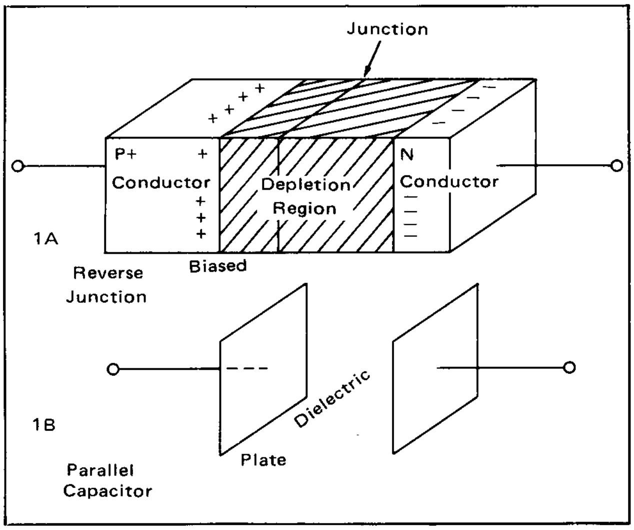

FIGURE 1 — Tuning Diode Capacitor Analogy

$$C = \frac{\epsilon A}{d} \qquad (1)$$

where ϵ = dielectric constant of silicon equal to $11.8 \times \epsilon_0$

$\epsilon_0 = 8.85 \times 10^{-12}$ F/m

A = Device cross sectional area

d = Width of the depletion layer.

The depletion layer width d may be determined from semiconductor junction theory.

The more accepted method of determining tuning diode capacitance is to use the defining formula for capacitance.

$$C = \frac{dQ}{dV} \qquad (2)$$

The charge, Q per unit area, is defined as:

$$Q = \epsilon E \qquad (3)$$

where E = Electric field

So we have capacitance per unit area:

$$c = \frac{C}{A} = \epsilon \frac{dE}{dV} \qquad (4)$$

Norwood and Shatz[1] use these ideas to develop a general formula:

$$c = \left[\frac{q B \epsilon^{m+1}}{(m+2)(V+\phi)}\right]^{1/m+2} \qquad (5)$$

m = Impurity exponent

c = Capacitance per unit area

Lumping all the constant terms together, including the area of the diode, into one constant, C_D, we arrive at:

$$C_J = \frac{C_D}{(V+\phi)^{\gamma}} \qquad (6)$$

where γ = Capacitance Exponent, a function of impurity exponent

ϕ = The junction contact potential ($\approx$ 0.7 Volts)

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The capacitance constant, C_D, can be shown to be a function of the capacitance at zero voltage and the contact potential. At room temperature we have:

$$C_D = C_o(\phi)^{\gamma} \tag{7}$$

C_o = Value of capacitance at zero voltage

The simple formula given in Eq. 6, very accurately predicts the voltage-capacitance relationship of Epicaps. There are many detailed derivations [1,2,3,4,5] of junction capacitance, so further explanation is not necessary in this note.

The capacitance of commercial tuning diodes must be modified by the case capacitance.

The equation then becomes:

$$C = C_c + C_J \tag{8}$$

where

C_c = Case capacitance typically 0.1 to 0.25 pF

C_J = Junction capacitance given by equation 6.

TUNING RATIOS

The tuning or capacitance ratio, TR, denotes the ratio of capacitance obtained with two values of applied bias voltage. This ratio is given by the following expression for the Epicap junction.

$$TR = \frac{C_J(V_2)}{C_J(V_1)} = \left[\frac{V_1+\phi}{V_2+\phi}\right]^{\gamma} \tag{9}$$

where $C_J(V_1)$ = Junction capacitance at V_1

$C_J(V_2)$ = Junction capacitance at V_2

where $V_1 > V_2$

In specifying TR, some Epicap data sheets use four volts for V_2. However, in order to achieve larger tuning ratios, the devices may be operated at slightly lower bias levels with some degradation in the Q specified at four volts. (See the discussion of Q versus voltage in the circuit Q section, later in this note). Furthermore, care must be taken when operating Epicaps at these low reverse bias levels to avoid swinging the diode into forward conduction upon application of large ac signals. These large signals may also produce distortion due to capacitance modulation effects.

Since the effects of ϕ and case capacitance, C_c, are usually small, Eq. 9 may be simplified to the following for most design work:

$$TR = \frac{C(V\text{min})}{C(V\text{max})} = \left(\frac{V\text{max}}{V\text{min}}\right)^{\gamma} \tag{10}$$

The frequency ratio is equal to the square root of the tuning ratio. This tunable frequency ratio assumes no stray circuit capacitance.

Another parameter of importance is γ, the capacitance exponent. Physically, γ depends on the doping geometry employed in the diode. Varactor diodes with γ values from 1/3 to 2 can be manufactured by various processing techniques. The types of junctions, their doping profiles, and resulting values of γ are shown in Figure 2. These graphs show the variation of the number of acceptors (N_A) and the number of donors (N_D) with distance from the junction.

Abrupt junctions are the easiest to manufacture and most Epicaps are of this type. This type of junction gives a γ of approximately 1/2 and a tuning ratio on the order 3 with the specified voltage range. Therefore the corresponding frequency range which may be tuned is about 1.7 to 1.0. A typical example is the MV2101:

$$C(V_2) = C(30\text{ V}) = 2.5\text{ pF}$$
$$C(V_1) = C(4\text{ V}) = 6.8\text{ pF}$$
$$TR = 2.7$$
$$\gamma = 0.47$$

The subscripts on the capacitance refer to the bias voltage applied.

In many applications, such as tuning the television channels, or the AM broadcast band, a wider frequency range is required. In this event, the designer must use a hyper-abrupt junction Epicap. The hyper-abrupt diode has a γ of 1 or 2, and much larger frequency ranges. Table I shows typical types of tuning diodes available, their tuning ratios, frequency ratios and junction types.

TABLE I SAMPLE TUNING DIODE TYPES

Device Series	Capacitances Available	Tuning Ratio	γ	Frequency Ratio	Junction Type
1N5139	47–6.8 pF	2.7–3.4	0.47	1.6–1.8	Abrupt
MV2101	100–6.8 pF	1.6–3.3	0.47	1.6–1.8	Abrupt
BB105	10 pF	4–6	1.0	2–2.4	Hyper-Abrupt
MV1400	550-120 pF	10-14	2.0	3.2-3.7	Hyper-Abrupt
MV109	30 pF	5-6.5	1.0	2.2-2.5	Hyper-Abrupt

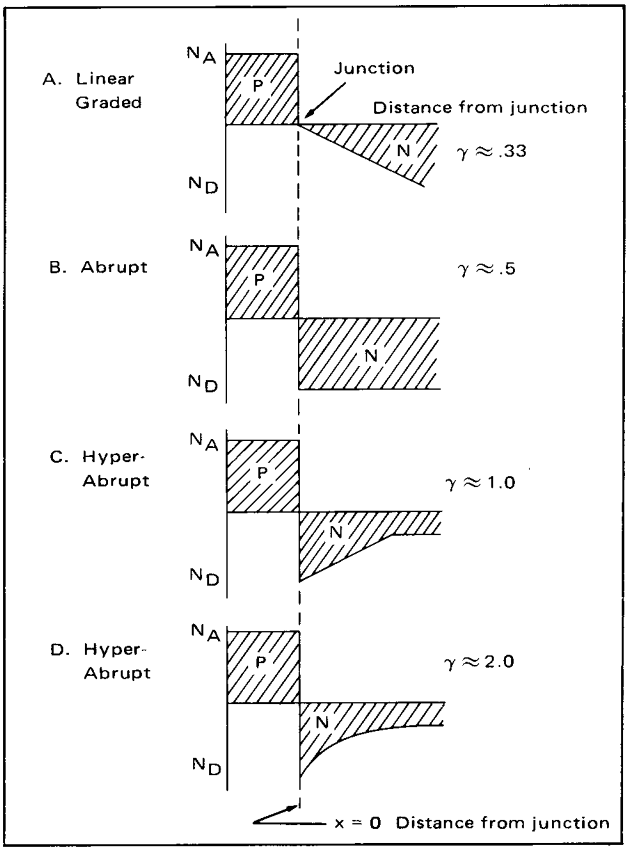


FIGURE 2 — Doping Profiles and Capacitance Exponent for Some Common Tuning Diode Types

The hyper-abrupt devices are constructed with special epitaxial growth and diffusion techniques, which creates a doping profile similar to that shown in Figures 2C and 2D. The Q of the BB105 and MV109 series hyper-abrupt diodes is as high as abrupt junction Epicaps. Their capacitance range is from a few picofarads to 10 or 20 pF, and their major application is in television tuners. The MV1400 series are high capacitance devices for applications below 10 MHz. They are suitable for tuning elements in AM broadcast band receivers and similar low frequency applications.

CIRCUIT Q

Popular types of mechanical tuning capacitors often have Q's on the order of a thousand or greater. The Q of tuned circuits using these capacitors is generally dependent only on the coil. When using an Epicap, however, one must be conscious of the tuning diode Q as well. The Q of the tuning diode is not constant being dependent on bias voltage and frequency. The Q of tuning diode capacitors falls off at high frequencies, because of the series bulk resistance of the silicon used in the diode. The Q also falls off at low frequencies because of the back resistance of the reverse-biased diode.

The equivalent circuit of a tuning diode is often described as shown: [7]

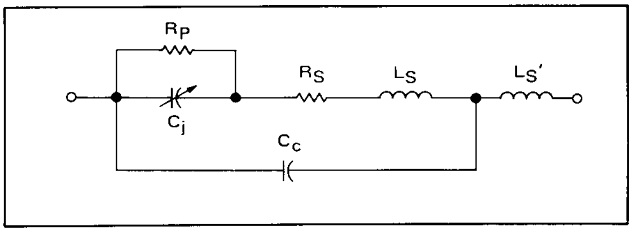


FIGURE 3 – Equivalent Circuit of Epicap Diode

where

R_P = Parallel resistance or back resistance of the diode
R_S = Bulk resistance of the silicon in the diode
L_S' = External lead inductance
L_S = Internal lead inductance
C_C = Case capacitance

Normally we may neglect the lead inductance and case capacitance. This results in the simplified circuit of Figure 4.

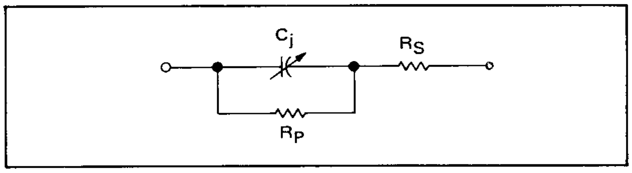


FIGURE 4 – Simplified Equivalent Circuit of Epicap Diodes

The tuning diode Q may be calculated with equation 11.

$$Q = \frac{2\pi fC\,R_p^2}{R_s + R_p + (2\pi fC)^2 R_s R_p^2} \qquad (11)$$

This rather complicated equation is plotted in Figure 5 for R_S = 1.0 ohm, $R_p = 30 \times 10^9$ ohms, at V = 4 volts and C = 6.8 pF, typical for a 1N5139 Epicap at room temperature.

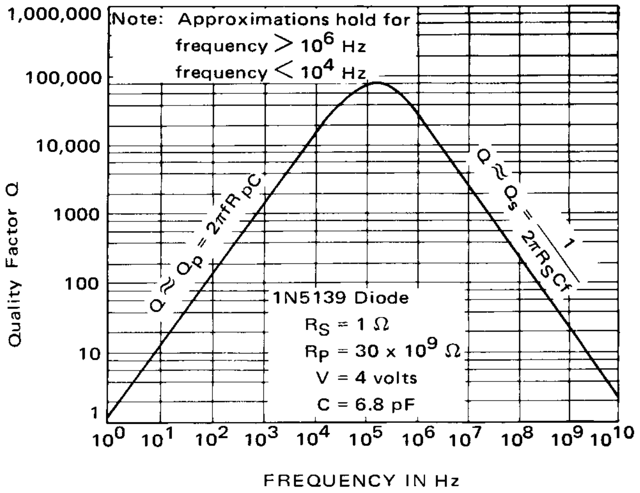


FIGURE 5 – Graph of Q versus Frequency

At frequencies above several MHz, the Q decreases directly with increasing frequency by the simpler formula given below:

$$Q \approx Q_S = \frac{1}{2\pi fCR_s} \quad \text{(High frequency Q)} \qquad (12)$$

The emphasis today is on decreasing R_s so better high frequency Q can be obtained. At low frequencies Q increases with frequency since only the component resulting from R_p, the back resistance of the diode, is of consequence.

$$Q \approx Q_P = 2\pi fCR_P \text{ (Low frequency Q)} \qquad (13)$$

Q is also dependent on voltage and temperature. Higher reverse bias voltage yields a lower value of capacitance, and also since R_s decreases with increasing bias voltage, the Q increases with increasing voltages. Similarly, low reverse bias voltages accompany larger capacitances, and lower Q's. Increasing temperature also lowers the Q of tuning diodes. As the junction temperature increases, the leakage current

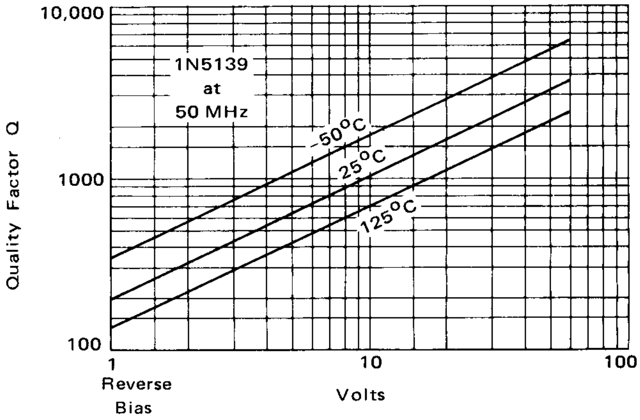


FIGURE 6 – Q versus Reverse Bias and Temperature

increases, lowering R_p. There is also a slight decrease in R_s with increasing temperature, but the effects of the decreasing R_p are greater and this causes the Q to decrease. The effects of temperature and voltage on the Q of a 1N5139 at 50 MHz are plotted in Figure 6.

TEMPERATURE

The Q and tuning ratio of Epicaps are parameters that every design engineer must be aware of in his circuits. Another equally important characteristic of tuning diodes is their temperature coefficient. A typical example of the capacitance versus temperature drift is shown in Figure 7.

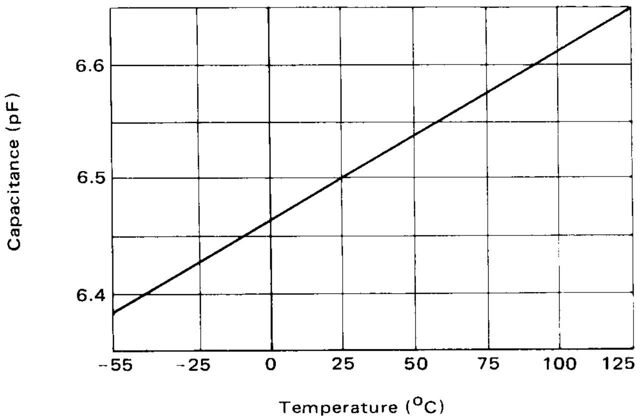


FIGURE 7 – Capacitance versus Temperature for a MV2101 Epicap Biased at 4 Volts

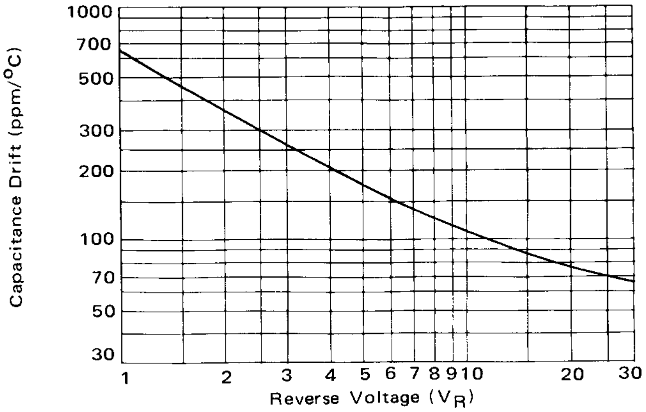


FIGURE 8 – Capacitance Drift in ppm/°C versus Voltage MV2101 Diode

The temperature constant, T_C, is a function of applied bias. Figure 8 shows T_C for a typical Motorola Epicap. Note that for low bias levels, on the order of a volt or two, the T_C is as high as +600 parts per million per degree centigrade (ppm/°C). This represents a frequency change of -300 ppm/°C which at 100 MHz means a frequency shift of 30 kHz per degree. It is obvious that a temperature compensation scheme is desirable for any frequency control not using feedback techniques.

In Figure 9, the actual capacitance drift of a MV2101 per degree centigrade is plotted. The graph illustrates that a simple negative temperature coefficient compensating capacitor will not compensate for the tuning diode T_C because the change in capacitance is not constant with voltage.

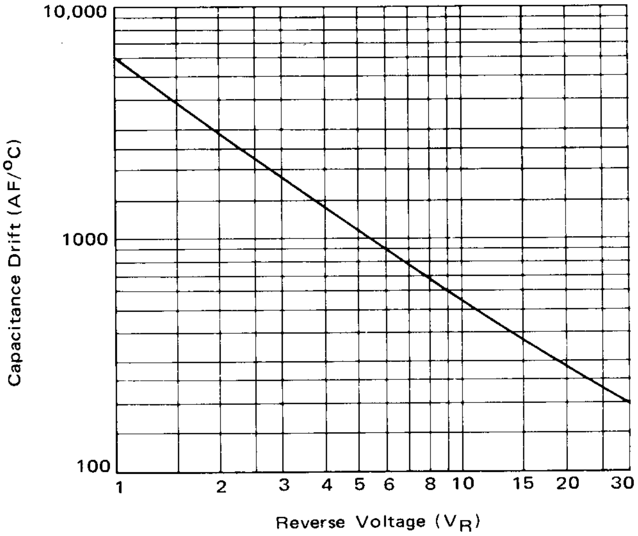


FIGURE 9 – Capacitance Drift in Attofarads/°C versus Voltage for the MV2101 Tuning Diode

Attofarads = (pF x 10^{-6})

A popular method of temperature compensating Epicaps involves the use of a forward biased diode. The voltage drop of a forward biased diode decreases as the temperature rises, thus applying a changing voltage to the Epicap. In the network shown in Figure 10, an increase in temperature will result in a decrease of the diode voltage V_{DIODE} to perhaps 0.5 V. If V_{in} is maintained constant, the available output voltage V_{out} will rise by 0.1 V. This increase in output voltage will lower the capacitance of the tuning diode and partially offset the initial capacitance increase caused by the temperature change. This method has been explored in detail and specific compensating circuits for Epicaps have been designed. The following sections describe the results of this work.

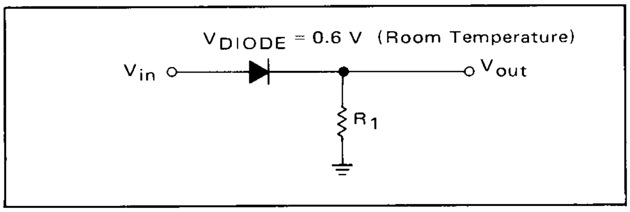


FIGURE 10 – Simple Temperature Compensating Network

THEORY OF TEMPERATURE CHANGE

Before proceeding further with schemes to correct the temperature drift, it is informative to investigate the physical mechanisms responsible for the changing capacitance. Equations 6 and 8 may be combined to give the basic expression for capacitance below:

$$C = \frac{C_d}{(V+\phi)^{\gamma}} + C_c \qquad (14)$$

We can pinpoint the terms in Eq. 14 that may account for capacitance changes. The contact potential, ϕ, is a strong function of temperature, varying on the order of -2 mV/°C. C_d is a function of geometric dimensions which can change with temperature and ϵ which changes with temperature. Case capacitance also changes with temperature. For this analysis we will assume the only terms not temperature dependent are the supply voltage V, and the capacitance exponent, which is a function only of the slope of the doping profile.

The contact potential, ϕ, is readily calculated from semiconductor theory, and the equations predict a large change with temperature. This change in ϕ will produce a much larger change in capacitance for lower voltages than for higher voltages, and therefore accounts for the majority of capacitance change in tuning diode temperature drift. See Table II.

TABLE II

Calculated capacitance change versus applied voltage in ppm/°C for:

$$\frac{d\phi}{dT} = -2\ \mathrm{mV/^{o}C}$$

$$C = \frac{C_d}{(V + \phi)^{\gamma}} + C_c$$

Applied Bias Voltage (Volts)	Capacitance Drift In (ppm/°C)
1	587
2	261
4	204
10	88.7
20	45.6
30	30.7

Comparing Table II with Figure 8, we see that a +40 to +50 ppm/°C temperature drift still remains. Therefore ϕ is not the only mechanism responsible for temperature drift and others must be sought. There is a change with temperature in physical dimensions in any material which has an affect on the order of 1 ppm/°C for a tuning diode. However, this change is too small to be of any significance. Another possibility is a change in dielectric constant. Silicon, depleted of its charge carriers, forms a dielectric layer with a relative dielectric constant of 11.8. The dielectric constant of silicon has a temperature coefficient of +35 ppm/°C. [1] These effects change the value of C_d with temperature.

Another effect which sometimes must be considered is the change in case capacitance with temperature. The case capacitance is about 0.25 pF for the plastic TO-92 case. And there is a change of +25 AF (attofarads = 10^{-6} pF) per degree centigrade. The glass DO-7 case exhibits a capacitance of about 0.20 pF and a change of +30 AF/°C. These are small changes for most low voltage capacitances, but become increasingly important as the voltage is increased and capacitance is reduced. Also these effects are only important for the low capacitance devices. For instance, consider the 1N5139 series which are packaged in the DO-7 glass case. Table III shows how large an effect case capacitance has on the capacitance drift of these diodes.

TABLE III Effect Of Case Capacitance Changes On 1N5139 And 1N5148 Epicaps

Bias Voltage (Volts)	1N5139 Capacitance (pF)	1N5139 Changes attributable to case capacitance (ppm/°C)	1N5148 Capacitance (pF)	1N5148 Changes attributable to case capacitance (ppm/°C)
2.0	8.9	3.4	61	0.5
4.0	6.4	4.7	47	0.6
10.0	4.8	6.3	32	1.0
30.0	3.0	10.0	19	1.6
60.0	2.2	14.0	13	2.3

In summary, the largest changes are caused by the change in contact potential. This effect is most noticeable at low voltage, high capacitance levels. The change in silicon dielectric is the next most important factor providing a change that is uniform for all devices and voltages. Case capacitance changes are most noticeable in the low capacitance, high voltage range, and may be neglected for all devices except those low capacitance devices.

THE POWER SUPPLY

We previously assumed that the supply voltage did not change with temperature. This is rarely the case, and special consideration must be given to this part of the design. All our efforts to temperature compensate the tuning diode may be in vain if the power supply has a large T_C or is otherwise unstable. Figure 11 shows the common method of supplying voltage to a tuning diode.

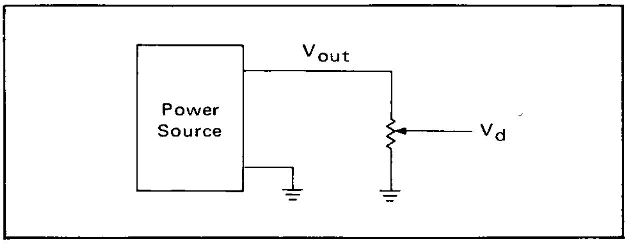


FIGURE 11 – Common Means of Supplying Bias Voltage to a Varactor Diode

POWER SOURCE

The power source is the most critical part of the circuit in Figure 11. It must be extremely stable in order to achieve good varactor tuning stability. The full drift of the power supply as expressed in ppm/°C will appear at V_d regardless of the setting of the potentiometer. For example, if V_{out} is 40 volts with a drift of 100 ppm/°C (4 mV/°C), V_d may be 10 V, but will still have a drift of 100 ppm/°C (1 mV/°C). A 50 ppm/°C stability figure in V_d translates into a 25 ppm/°C stability of capacitance, when the capacitance exponent is 0.5. For hyper-abrupt junctions we realize capacitance stabilities of 50 and 100 ppm/°C for exponents of 1 and 2 respectively.

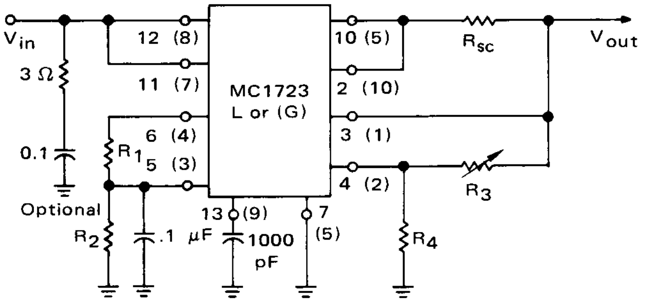
There are many differing power supply regulators available to the designer. Zener diodes are relatively inexpensive, but have a poor temperature coefficient. Temperature compensated zeners are very expensive and have a limited voltage range. The MC1723, a monolithic integrated circuit voltage regulator, has excellent temperature characteristics, 37 volt output capability, and wide temperature range.

TABLE IV Summary of Power Regulators

Device	Voltage Range	Temperature Range	Voltage ppm/°C Max T_C	Voltage ppm/°C Typical T_C	Capacitance ppm/°C Typical $\gamma = 0.5$	Relative cost
1N5260 Zener	33	-65 +200°C	975	975	475	Low
1N4752 Zener	33	-65 +200°C	850	850	425	Low
1N3157 Temperature Compensated Zener	8.4	-50 +125°C	10	10	5	High
MC1723 Regulator	37	-55 +125°C	20	12	6	Medium
MFC6030 Functional Regulator	32	0° +70°C	50	15	7.5	Low
MC7800 Fixed Voltage Regulators	28	0° +125°C		40-60	20-30	Medium
MVS460 TO-92 Regulator	31 V	0 +70 °C	-100 +50	-25	12	Low

Notes:
1) See Figure 12 for some typical circuit connections
2) More information on regulators is available in literature 8,9,10
3) To compute frequency change (ppm/°C), divide capacitance (ppm/°C) change by 2.

(If 60 V_{out} is required, use of a voltage boost circuit is needed)

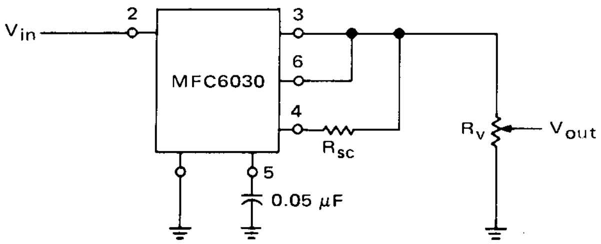


Numbers in parenthesis refer to G package.

R_{sc} 10 Ω ½W 10%
R_1 5 kΩ 1% } {Accurately Match T_C to within better
R_2 2 kΩ 1% } { than 20 ppm/°C.
R_3 0-50 kΩ 50 ppm/°C potentiometer
R_4 2 kΩ 1% 20 ppm/°C

V_{in} = 40 V
V_{out} variable 2-37 Volts

FIGURE 12A – High Stability Regulator -50 to +125°C



V_{in} = 35 Volts max
R_{sc} = 20 Ω ½W 10%
R_v = Variable Resistor feeding the Epicap
$R_v \approx$ 50 k 50 ppm
V_{out} 0-33 Volts

FIGURE 12 B – Regulator Using MCF6030, 0° – 70°C

The MFC6030 Functional* integrated circuit is less costly and exhibits almost as good a temperature constant.

The MC7800 fixed output voltage regulators are extremely simple to use in that they have only input, output and ground terminals and require no external components other than possibly a high frequency bypass capacitor. (The latter item is generally required with all IC regulators to prevent high frequency oscillations).

The MVS460 is a two leaded IC regulator especially designed for use with tuning diodes. It represents a simple, inexpensive solution to the voltage regulator problem. Table IV contains a summary of available power supply regulators.

VARIABLE RESISTOR

The variable resistor is considerably less critical. Since it is being used as a voltage divider, all that is required is that the resistive material be uniform so any change in resistance is uniform throughout the potentiometer. Wire wound, and special high quality cermet film variable resistors are suitable for these applications. Generally speaking, a linear potentiometer should have a T_C of ±150 ppm/°C or better. Special taper potentiometers should have a T_C of ±50 ppm/°C or better.

The variable resistance cannot be made too large or there will be appreciable voltage drop as the reverse current in the diode increases. The reverse current in a silicon diode generally doubles every 10°C so this becomes an important problem at temperatures above 50°C. If the temperature is expected to run as high as 70°C, one must limit the variable resistor to 50 kΩ or the effect will be a greater than 5 ppm/°C capacitance change. If 50°C is the upper temperature limit, the resistance may be upped to 150 kΩ. These values apply to all of Motorola's Epicap series. When the tuning diodes are used in applications where temperature will greatly exceed 70°C, the divider resistance should be kept below 10 kΩ. This low value requires large power supply currents and would be undesirable in some applications. However, since the Motorola MC1723 is the recommended power source at these temperatures, voltage control may be accomplished using the regulator without relying on an external divider potentiometer, as shown in Figure 12A. The MC1723's low output impedance of 0.05 ohms will easily and reliably handle the change in current demanded by the Epicap as it heats up. Figure 12B shows another popular regulator circuit. If higher or lower voltages are needed, schemes such as voltage boost[8] and floating regulators may be used.

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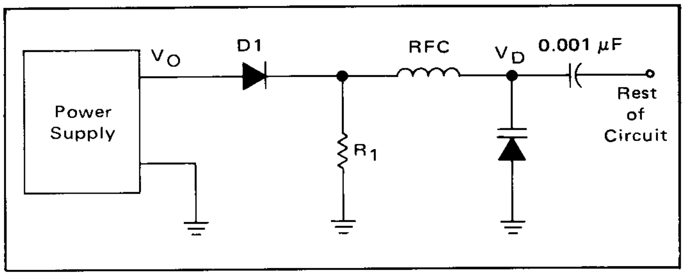


FIGURE 13 — Temperature Compensation Using A Silicon Diode

TEMPERATURE COMPENSATION

It has been previously noted that the most effective means of temperature compensation is simply to use a silicon junction biased in the forward direction. A circuit employing this technique is shown in Figure 13.

Diode D1 has a forward voltage drop on the order of 0.6 volts, and a temperature coefficient of -0.002 V/°C. Assuming a constant voltage from the supply, the reduction in diode voltage with increasing temperature, increases the voltage available to the tuning diode, V_D. The higher tuning diode voltage, V_D, lowers the capacitance enough to compensate for the increase due to temperature. However, merely using a random diode with an arbitrary value of R1 will not result in very accurate temperature compensation.

Different correction devices exhibit different T_C (changes in voltage drop with temperature) values because of differing doping schemes. For example, a typical Epicap exhibits a T_C of approximately – 1.5 mV/°C while some high current rectifier junctions measure as high as -2.6 mV/°C. So it is necessary to investigate many different junction devices in order to find a diode that adequately compensates the tuning diode drift.

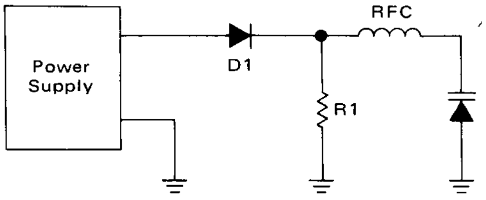
The tuning diode's change with temperature must be accurately determined. Also of major importance is the value of R1. A typical junction may have a T_C of -1.5 mV/°C at 10 mA junction current, and a T_C of -2.8 mV/°C at 1 µA junction current. Thus the value of R1, the bias resistor, must be chosen to yield the optimum value of compensating diode current.

Detailed analysis was performed on 160 low cost junction devices in order to arrive at suitable compensation schemes for Motorola's Epicaps. The results appear in Table V. The correction diodes represent the devices which provided the most accurate and reliable compensation. A computer program was devised to optimize the value of R1 in each case. Two different methods of compensation were analyzed. Method one searches for the lowest ppm values without using C1, the temperature compensating capacitor. At some voltages the temperature corrected tuning diode will have a negative temperature coefficient, while at others it will be positive. In general the results are better than ±50 ppm over the entire range from 2 volts to the breakdown voltage of the Epicap diode.

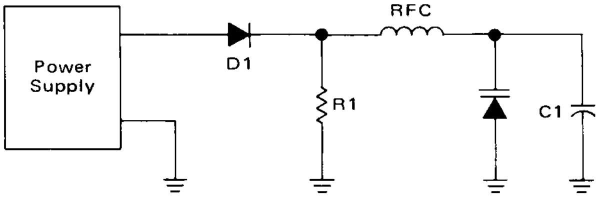
TABLE V

Tuning Diode	Correction Diode	Method One R1	Typ ppm Method One -50 to 125°C	Max ppm Method One -50 to 125°C
MV2101 Series	MSD6100	50 k to 70 k	-30 to +40	±50
	1N4001	20 k to 30 k	-40 to +40	±60
	*2N5221	250 k to 400 k	-30 to +40	±55
	*MPS5172	250 k to 400 k	-35 to +40	±60
	*MPS3904	—	—	—
1N5139	MSD6100	400 k to 600 k	-30 to +50	±60
Series	1N4001	400 k to 600 k	-30 to +45	±50
	MPS5172	—	—	—
MV2305 Series	MSD6100	40 k to 60 k	-40 to +50	±60
Note 2	1N4001	15 k to 25 k	±45	±65
	*2N5221 *MPS5172	250 k tp 350 k	±45	±70
	*MPS3904	—	—	—
MV3500 Series	MSD6100	30 k to 40 k	±40	±60
	*2N5221 *MPS5172	120 k to 180 k	-35 to +45	±55
	*MPS3904	—	—	—
1N5441 & 1N5461 Series	MSD6100	400 k to 500 k	±45	±60
	1N4001	400 k to 500 k	±50	±60
	*2N5221 *MPS5172	—	—	—

*Base-Emitter junction used as a diode.



METHOD ONE — Schematic Diagram



METHOD TWO — Schematic Diagram

Note 1: To find the value of negative temperature coefficient capacitor, C1, use equation 15.

$$C_1 = \frac{C_x \cdot C_{TD}}{N} \text{ in pF} \qquad (15)$$

where

C_x = Value listed above in Table V
C_{TD} = Capacity in pF of the tuning diode at four volts
N = Temperature coefficient of capacitor.
If a N750 is used, N = 750.

Note 2: For MV2305 series, the ppm/°C drift values specified hold for 1.5 V to the breakdown voltage.

Method two attempts to cluster the residual capacitance at some standard value after the diode has performed its correction. This value (due to silicon dielectric change, case capacitance change, etc.) is easily "tuned out" by means of a small negative temperature coefficient capacitor.

Method Two R1	Method Two C_x Note 1	Typ ppm Method Two -50 to 125°C	Max ppm Method Two -50 to 125°C
8.2 k	23	±15	±25
—	—	—	—
33 k	23	±15	±25
47 k	23	±15	±25
180 k	23	±20	±30
120 k	16	±25	±35
82 k	15	±20	±30
600 - 800 k	15	±25	±35
—	—	—	—
—	—	—	—
18 k	35	±15	±25
100 k	34	±15	±25
—	—	—	—
—	—	—	—
56 k	22	±15	±25
68 k	22	±20	±30
22 k	22	±20	±30
390 k	22	±20	±35

Consideration must be given to the stability of R1. As the resistance of R1 increases with changing temperature, less current will be drawn through D1, thus decreasing its voltage drop. The result will be a rise in the voltage applied to the Epicap. Analysis of this effect is shown in Table VI.

The results of using a MV2111 in the compensation circuits are shown in Figures 14A and 14B. Only the diode, resistor R1, tuning diode, and capacitor C1 if used were subjected to temperature changes. Thus, any effect of power supply variation and variable resistor instability were neglected.

TABLE VI

TUNING DIODE BIAS VOLTAGE

ppm Accuracy of R1	1 V	2 V	5 V	25 V	
±10 ppm	1	1	—	—	PPM CAPACITANCE CHANGE
±25 ppm	3	2	1	—	
±50 ppm	6	4	2	1	
±100 ppm	12	7	4	2	
±200 ppm	24	14	8	4	

Keeping cost in mind, ±100 ppm or ±50 ppm 1% resistors are recommended for R1.

Actual circuits constructed will not be as accurate as these test results because the power supply and variable resistor will contribute some instability. Some of the variations that will occur are shown in Table VII.

The effects of tuning diode variation and correction diode variation are accounted for in Table V. The effects of power supply and potentiometers must be accounted for separately and decrease the total accuracy. If a ±25 ppm/°C correction scheme is used, but the power supply has ±25 ppm/°C stability, an overall stability of ±35 ppm is obtained. This apparent error results from the fact that the error factors cannot be added directly, but must be summed as vectors in accordance to the rules of error theory. It is important to consider the whole circuit when designing for temperature compensation.

TABLE VII Other Error Contributing Factors In Temperature Compensation

	Typical ppm/°C
Power Supply Variation	±8
R1 Changes	±5
Changes in Epicap Current through Potentiometer	±5
Potentiometer Nonlinearities	±2
Tuning Diode Variation	±10
Correction Diode Variation	±15

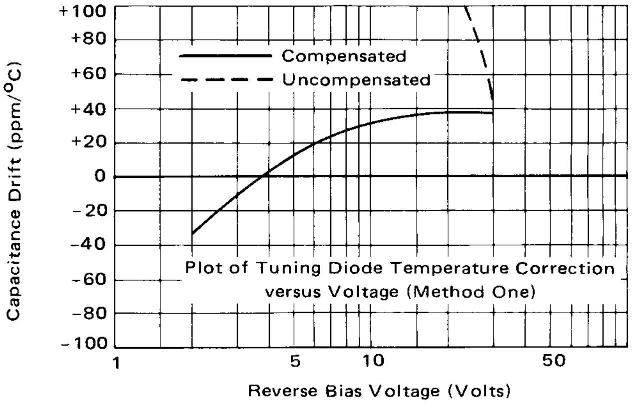


FIGURE 14A – MV2111, MSD6100 Compensation Diode R1 = 68 k

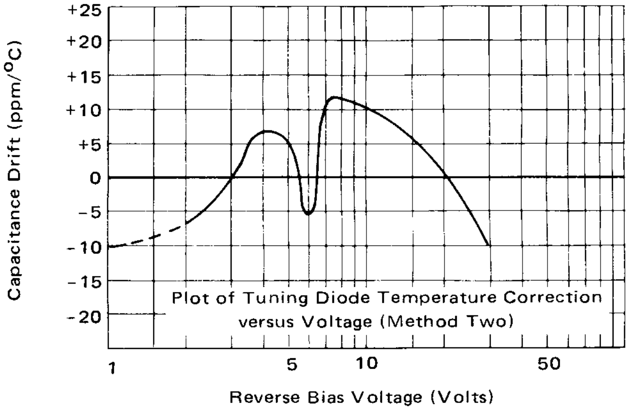


FIGURE 14B – MV2111, MSD6100 Compensating Diode
R1 = 8.2 k
C1 = 3.3 pF (N330)
0.00109 pF/°C

HYPER-ABRUPT TEMPERATURE DRIFT

The hyper-abrupt tuning diode is more sensitive than other types to temperature variations resulting in a greater need for temperature compensation. Also their drift with temperature is not as uniform as abrupt junction tuning diodes. Their drift factors expressed in ppm/°C run as high as 800 to 1200 for the units with a γ of 2. Units having a γ of 1 typically show 300 to 400 ppm/°C capacitance changes. These higher drift rates are caused by the hyper-abrupt tuning diode's greater sensitivity to changes in voltage, and the fact that the majority of capacitance change is caused by the change in contact potential, ϕ. This greater sensitivity to voltage changes means that power supply and other instabilities will also have a larger effect than with regular abrupt junction tuning diodes.

As a first order approximation, a MPS3904 transistor's emitter-base junction with a 50 k resistor used for R1 will improve the temperature drift in capacitance to better than 200 ppm/°C. Improvement from this point can only be obtained by a trial and error method described below.

Figure 15 shows the variation in compensation as R1 is varied for the MV3142, a hyper-abrupt tuning diode. As R1 is increased in value, the ppm/°C value is made more negative. The effect of the change is greatest at lower voltages.

To completely compensate the drift factor of the MV3142 shown in Figure 15 would be very difficult due to the variation of the curve shape. However, improved compensation may be achieved by limiting the diode to an operating voltage range of 2 to 15 volts. Starting with an R1 value of 50 k, the tuning diode and compensation circuit should be varied in temperature, while measuring the capacitance change. If the drift factor is more positive than desired, R1 may be increased in value. Referring to Figure 15, a temperature drift factor of +40 ppm/°C at 2 V may be larger than can be tolerated. Substituting a 200 k resistor will reduce the value to 25 ppm/°C at 2 V. In order to accurately compensate at any voltage, it is only necessary to vary R1 while measuring the capacitance drift. If the required value for R1 becomes larger than 750 k, the compensating junction type should be switched to a MSD6100, and the bias resistor started at 50 k again.

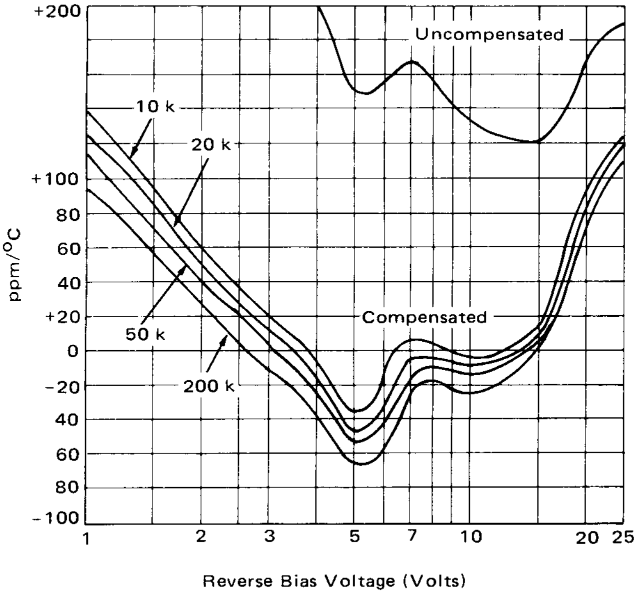


FIGURE 15 – MV3142 Tuning Diode Compensation For Differing Values of R1

SUMMARY

Voltage variable capacitors are rapidly replacing air variable capacitors in many applications. These devices offer many advantages over previous variable capacitors, such as the ability to employ remote tuning. By carefully considering the proper design conditions, such as temperature drift, and designing accordingly, Epicaps can replace air capacitors in virtually all but high power applications. The designer must be aware of the tuning range and Q limitation in order to use these devices effectively. Temperature drift should cease to be a problem when proper compensation schemes are used.

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