A TABULATION OF VOLTAGE-VARIABLE CAPACITORS

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Electronic Defense Group
Department of Electrical Engineering

T. W. Butler, Jr.            Approved by: H. W. Farris
G. A. Roberts

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ABSTRACT

A tabulation of voltage-variable capacitors is presented. The various types of capacitors available, the frequency ranges in which they will operate, types of circuits in which they can be used, and other pertinent operating characteristics are presented.

In addition, a clarification of the distinction between the ferroelectric capacitor and the back-biased diode with regard to the principle of operation is presented.

It should be noted that the list of manufacturers is not exhaustive but can be considered as representative.
A TABULATION OF VOLTAGE-VARIABLE CAPACITORS

1. INTRODUCTION

Increasing interest in the use of voltage-variable capacitors for electronic frequency control has resulted in a number of queries as to what types are available, frequency ranges in which they will operate, types of circuits in which they can be used, and other pertinent operating characteristics. In many cases several different types could be used, each having somewhat different performance characteristics. The type of voltage-variable capacitor which is most suitable, whether it be ferroelectric or back-biased diode, can be chosen on the basis of a logical evaluation.

The choice will involve simultaneous consideration of several factors for each available type of capacitor in terms of the basic requirements of the circuit in which it is to be used.

2. OPERATING CHARACTERISTICS - FERROELECTRICS AND BACK-BIASED DIODES

A clarification of the distinction between the ferroelectric capacitor and the back-biased diode with regard to the principle of operation appears desirable. The following brief discussion is for this purpose.
In the case of the silicon junction diode, the density of charge carriers at a P-N junction (electrons in the N-region and holes in the P-region) is reduced almost to zero as a voltage is applied in the reverse direction across the junction. This region of zero charge-density, known as the depletion region, is not only swept clear of charge carriers but actually widens as the reverse bias is increased. In effect, the two conducting areas appear to act as two metal plates, which tend to move farther apart as the reverse bias is increased. The plate area and the dielectric constant remain the same, but the distance between the plates varies according to the applied voltage.

When these back-biased diodes are used in a resonant tank-circuit where high RF voltages may be developed across them, the junction must be back-biased far enough so that no part of the signal-voltage swing causes the net voltage applied to the junction to go positive, or clipping will result. This effect can be avoided at the expense of reducing the circuit Q somewhat by placing two back-biased diodes in series opposition across the tank coil.

In the case of ferroelectrics, the method of operation is completely different. Ferroelectricity can be described as a spontaneous polarization. Polarization in dielectric materials may be due to:

1. Alignment of permanent electric dipoles,
2. Displacement of the + and − ions relative to one another (e.g., Na$^+$ and Cl$^-$ in NaCl), or
3. Displacement, relative to the positive nucleus, of the center of gravity of the negative charge of the electrons.
Ferroelectricity will occur if any of these mechanisms, either singly or in combination, occurs spontaneously, i.e., without the application of an external electric field. A number of materials exhibit ferroelectricity, but on the whole the phenomenon is rather rare. Barium titanate (BaTiO$_3$) is, from a practical point of view, the most important ferroelectric and, when mixed with a nonferroelectric buffer material such as strontium titanate, becomes a suitable material for many practical applications.

Although the mechanism of spontaneous polarization which describes ferroelectricity is somewhat complicated, the basic properties may be stated simply. In the ceramic of which practical capacitors are formed, the barium titanate is made up of a multitude of tiny particles whose spontaneous dipoles are randomly oriented. Therefore, the statistical average of the elemental orientations is zero, and there is no net polarization before application of an electric field. When a dc bias is applied to the material, some of the dipoles originally randomly oriented will align themselves with the field; consequently, the dielectric constant decreases. As the biasing field is increased, more and more dipoles are reoriented, and the dielectric constant continues to decrease until saturation is reached, i.e., until a further increase in bias fails to produce a proportionate increase in polarization. This presumably occurs as a result of the exhaustion of the supply of randomly-oriented dipoles.

Unlike the back-biased diodes, the ferroelectric capacitors can be biased in either the positive or negative directions, and clipping will not result when they are used in a resonant circuit.

Figure 1 compares the capacity-vs-voltage curves at 100 mc of an inexpensive commercially-available back-biased diode and the Michigan Ferroelectric Capacitor. These two curves have been normalized to
FIG. 1  TYPICAL CAPACITY VS VOLTAGE CURVES AT 100 MC (NORMALIZED)

<table>
<thead>
<tr>
<th></th>
<th>100% CAPACITY</th>
<th>100% BIAS</th>
<th>TEMP</th>
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</thead>
<tbody>
<tr>
<td>DIODE</td>
<td>25 pf</td>
<td>130 VOLTS</td>
<td>27°C</td>
</tr>
<tr>
<td>FERROELECTRIC</td>
<td>125</td>
<td>170 VOLTS</td>
<td>27°C</td>
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</tbody>
</table>

UNIVERSITY OF MICHIGAN FERROELECTRIC CAPACITOR

HUGHES (HC 7001) BACK-BIASED-DIODE CAPACITOR
compare their characteristics. The small table at the top right gives the actual values for the components. The two curves were normalized for the maximum capacitance range of the diode. Other comparisons can readily be made. Figure 2 compares the Q-vs-voltage curves at 100 mc of the same back-biased diode and the Michigan Ferroelectric Capacitor, while Fig. 3 compares the capacity-vs-temperature curves of the same two voltage-variable capacitors. Note that the last two curves are not normalized.

3. TABLE AND RELATED COMMENTS

The list of manufacturers is not exhaustive, but it can be considered as representative (see Fig. 4). Some of the units listed are experimental and not commercially available. In the ferroelectric field almost any manufacturer of high-dielectric-constant ceramic capacitors should be able to provide capacitors with some degree of voltage sensitivity.

Unless otherwise stated, initial capacitance is the small-signal capacitance that exists when the device has zero bias. When bias is the independent variable and other parameters are held fixed, the small-signal capacitance appears to be a maximum at approximately zero bias for both the diode and ferroelectric.

The frequency range of the device is the typical range in which the device may find application.

Minimum capacitance is the small-signal capacitance that occurs when the device has maximum bias applied.
FIG. 2  TYPICAL Q VS VOLTAGE CURVES
AT 100 Mc.
FIG. 3 TYPICAL CAPACITANCE VS TEMPERATURE CURVES
## Back Biased Diode Capacitors

<table>
<thead>
<tr>
<th>MANUFACTURER</th>
<th>TYPE</th>
<th>INITIAL CAPACITANCE</th>
<th>MINIMUM CAP</th>
<th>MAXIMUM VOLTAGE</th>
<th>Q</th>
<th>CUTOFF FREQ.</th>
<th>R SERIES</th>
<th>TEMPERATURE SENSITIVITY</th>
<th>COMMENTS</th>
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<tr>
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<tr>
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<td>55</td>
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### Back Biased Diode Capacitors

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<th>INITIAL CAPACITANCE</th>
<th>MINIMUM CAP</th>
<th>MAXIMUM VOLTAGE</th>
<th>Q</th>
<th>CUTOFF FREQ.</th>
<th>R SERIES</th>
<th>TEMPERATURE SENSITIVITY</th>
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<td>WESTERN ELECTRIC</td>
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<tr>
<td>Sylvania</td>
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<td>TRANSISTOR</td>
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### Ferroelectric Capacitors

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<tr>
<th>MANUFACTURER</th>
<th>TYPE</th>
<th>INITIAL CAPACITANCE</th>
<th>MINIMUM CAP</th>
<th>MAXIMUM VOLTAGE</th>
<th>Q</th>
<th>CUTOFF FREQ.</th>
<th>R SERIES</th>
<th>TEMPERATURE SENSITIVE CURVE 30°C</th>
<th>EXPERIMENTAL UNIT</th>
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</thead>
<tbody>
<tr>
<td>UHF TO AUDIO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>205</td>
<td></td>
<td></td>
<td>CAPACITY VARIATION 8X TO 10X FOR A TEMPERATURE RANGE OF -40°C TO +60°C, CURVE 12°C AT 25°C</td>
<td>EXPERIMENTAL UNIT</td>
</tr>
<tr>
<td>VHF TO AUDIO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>98</td>
<td></td>
<td></td>
<td>CURVE = 22.5°C ± 5% @ 300°C FOR +4°C TO +30°C</td>
<td>EXPERIMENTAL UNIT</td>
</tr>
</tbody>
</table>

### Ferroelectric Materials May Be Available from These Manufacturers: AEROVOXY, CENTRALAB, MULLENBACH, SPRAGUE, AND OTHERS

**FIG.4 Tabulation of Voltage-Variable Capacitors**
Maximum voltage is the highest bias voltage at which the device can be operated. In the case of the diode it is the maximum peak inverse-voltage. The maximum voltage for the ferroelectric is determined by its dielectric strength.

$Q$ is the energy-storage figure of merit. For a capacitor $Q$ may be expressed as $1/(wR_s C)$, where $R_s$ is the equivalent series resistance.

Cutoff frequency, $f_c$, is defined as $\frac{1}{2\pi R_s C_{min}}$. Specifications of $f_c$ are based on a measurement of $R_s$ and $C_{min}$ at some frequency below $f_c$, then $f_c$ is calculated. Recent investigations indicate that $R_s$ may not be a constant; in this event, $f_c$ would not be given by the above equation.

$R_s$ is the equivalent series-resistance of the device. For diodes, this is assumed to be a constant. For ferroelectric capacitors, however, no simple relationship for $R_s$ as a function of the frequency is known, although it can be assumed constant at a given frequency.

Temperature sensitivity is used here as a measure of the response of the component to incremental temperature changes. The performance of diode capacitors shows only a slight dependence upon temperature, whereas that of the ferroelectrics is quite sensitive to temperature. Storage-temperature or wiring-temperature of the ferroelectric capacitor is limited by the method of attachment of the leads to the ceramic, which is usually done with ordinary solder.

In general, all of the devices may be used as tuning elements in oscillators and filters. The maximum power-level is a function of the device, the frequency, and the tuning range. Ferroelectrics have been used in oscillators for tuning, with a power output of 0.4 watt at
400 mc with a 20 mc tuning range, showing a negligible shift in capacitor characteristics due to heating of the capacitor by dielectric losses.

Other general applications so described in the references are in parametric amplifiers, modulators, adjustable delay-lines, tunable antennas, thermometers, frequency converters, and distributed-variable devices. Some specific applications are in FM modulation, automatic frequency-control, electric receiver-tuning, panoramic-receiver tuning, tunable audio-oscillators, and tunable filters.

The frequency range of the device is a function of its Q and the range of capacitance values that can be fabricated. That diodes can be made which have high Q's at high frequencies is illustrated by the Bell diode. Ferroelectrics can not now compete in this field. The Q of a good ferroelectric under the best conditions may be 4 at 3000 mc. In the future better ferroelectric materials may be developed.

The maximum capacity of a ferroelectric can be large. For instance, an initial capacitance of 0.1 μfd can be attained with a slab approximately 1.2 x 1.2 x 0.1 cm in size. Fabrication of a diode of this capacitance value would be difficult.

Both diodes and ferroelectrics are physically small components. For instance, a diode with an initial capacitance of 88 μufd can be packaged in a case 0.25" long x 0.1" in diameter. A ferroelectric capacitor of 100 μufd can be packaged in a plastic sphere about 0.1" in diameter.

The cost of diodes in small quantities ranges from about one dollar to several hundred dollars. Because of the complexity and non-homogeneity of diodes it is reasonable to expect that their minimum
price will remain at about the one-dollar level. The ferroelectrics are inherently easier to fabricate and therefore should have a lower price.

Some applications require tracking of several circuits. The characteristics of diodes will vary significantly from one unit to another and introduce tracking problems unless units are selected. With ferroelectric capacitors it is possible to make all units for a given circuit from the same ceramic wafer, which results in good tracking of the capacitors.

4. COMMENTS CONCERNING MANUFACTURERS' CURVES

Both diodes and ferroelectrics have complex characteristic-curves. It appears that manufacturers, in an attempt to simplify the data, have left out information that is important. The result is that persons unfamiliar with the device may be misled. In general both diodes and ferroelectrics have capacitance that is a function of bias and temperature, and Q as a function of bias, temperature, and frequency. Some diode manufacturers tabulate Q at a specific frequency at maximum bias and fail to indicate the Q at zero bias or describe the law for Q. Assuming that $R_o$ is independent of bias and that the initial capacitance is 10 times the minimum capacitance, a minimum Q of 1/10 the tabulated value is given. It is also necessary to consider signal level relative to the bias voltage for, if a diode is driven into conduction, the Q will drop and the effective capacitance will change.
In presenting data on ferroelectrics some manufacturers plot percent capacitance change vs bias, with temperature as a parameter and all curves starting at zero bias and 100% capacitance. This tends to give a misleading picture of the temperature characteristics. The \( \varepsilon-T-E \) surface in Fig. 5 is a more descriptive type of presentation.

5. CONCLUSIONS

In conclusion it should be reiterated that the tabulation is not exhaustive but merely representative. It would seem that a complete listing of all the available diodes which might possibly be used in reactance and other voltage-tunable devices would make the tabulation very unwieldy indeed.

In general, recommendation of a particular diode for a specific purpose was avoided, since it was considered likely that the reader might then be biased against using that diode for other applications. It is perhaps more beneficial to require the reader to study the characteristics and make his own choice for a particular application.
- $E_{dc} = 0.005 \text{KV CM}^{-1}$ RMS AT 1KC
- CYCLING FIELD ONE POLARITY
- CYCLING FIELD RATE = 100 KV CM\(^{-1}\) MN\(^{-1}\)
- DATA PLOTTED ONLY FOR $E_{dc}$ INCREASING

**E-T-E SURFACE**

FOR AEROVOX "HQ"-91

FIG. 5
REFERENCES


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