A novel, low-power Capacitive Waveform Transformer

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Abstract—Considerable activity is going on in the area of microelectronics from the point of reducing power dissipation. Capacitors in general being non-dissipative elements, it is thought that circuits with only capacitive devices might reduce power dissipation to the minimum. In the present paper, synthesis of a nonlinear capacitor (which is an important part of any waveform shaping circuit) is carried out using the conventional, uniformly doped MOS capacitors, and as an example, the non-linear capacitor required for the \( \mu \)-law compander is attempted at. Also, as an application in waveform shaping, we have discussed in detail, the transformation of a sinusoidal waveform to a triangular waveform.

Keywords—MOS Capacitor, waveform transformation.

I. INTRODUCTION

Waveform transformation or shaping is often required to implement many electronic functions. This is usually done through digital techniques or by the use of operational amplifiers\cite{1}. These transformations can also be carried out through the use of appropriate nonlinear circuit elements. However, one should have a methodology of obtaining precisely the required characteristics like the I-V characteristics of a nonlinear resistor. One such technique is reported using shaped super conductors\cite{3}, where the required I-V characteristics are obtained by suitably shaping a super conducting film. A new and interesting way to realize wave modification using non-linear voltage dependent capacitors has been reported by Bipul\cite{4}, in which non-linear capacitor is designed by doping the MOS capacitor in a particular way, depending on the C-V characteristics to be obtained. This paper illustrates a simple technique to design any non-linear capacitor using the standard, uniformly doped \textit{p}-MOS and \textit{n}-MOS capacitors. Physical parameters of the MOS capacitors required for designing a \( \mu \)-law compander has been worked out to emphasize the practical feasibility of the technique. Also described is a method of implementing waveform transformers using a capacitive device.

II. PRINCIPLE

The Q-V characteristics of the desired non-linear capacitor can be obtained by simple integration of the C-V characteristics, which is assumed to be known. This Q-V characteristics is then segmented along the voltage axis. The error in approximation depends on this segmenting and for simplicity, we assume that the Q-V curve is linear in each segment. Now, consider a device with Q-V characteristics as shown in the figure(1) with varying \( V_A, V_B \) and \( C_0 \). By connecting these devices in parallel we get a non-linear capacitor with piecewise linear parts. This is shown in figure(2).
These devices are a simple series combination of standard \( p \)-MOS and \( n \)-MOS capacitors, with different physical parameters, but the same doping and oxide thickness.

![Graphs of charge vs voltage for series and parallel combinations of capacitors.](image)

**Fig. 2.** Parallel combination of capacitors

**III. DISCUSSION**

To get the \( Q-V \) curve of the series combination of \( n \)-MOS and \( p \)-MOS capacitors we note that

\[
V(n) = F(Q) \tag{1}
\]

\[
V(p) = G(Q) \tag{2}
\]

and for the series combination,

\[
V = V(n) + V(p) \tag{3}
\]

at charge \( Q \). Poisson’s one-dimensional equation can then be solved for this system, or, we can also, for different values of \( Q \), find, \( V(n) \) and \( V(p) \) graphically and the voltage \( V \) is thus calculated corresponding to \( Q \). A general variation of \( Q \) vs \( V \) is shown in the figure(3). Note that we have got the \( Q-V \) curves by integrating the HFCV curves of the \( n \)-MOS and \( p \)-MOS capacitor[2]. We shall henceforth refer this device as \textit{capacitor-doublet}.

From the figure(3) it may be seen that the crucial points, \( V_A \) and \( V_B \) are given by[5]

\[
V_A = V_n \tag{4}
\]

\[
V_B = V_n + 2V_p \tag{5}
\]

\[
C_o = C_{max}/2 \tag{6}
\]

where, \( V_n \) and \( V_p \) are the points at which the change in slope is assumed to occur in the \( p \) and \( n \) characteristics, and are essentially the threshold voltages[2], and hence, just by controlling the physical parameters like \( \phi_m \) and the bulk charge, we can get doublets with different values of \( V_A \) and \( V_B \). \( C_o \) can then be controlled by cross-section area of the MOS capacitors. Here, symbols have their standard meaning.

We now calculate device parameters of the various MOS capacitors required for the non-linear capacitor in the \( \mu \)-law compander

**IV. DESIGN OF NONLINEAR CAPACITOR BANK FOR A \( \mu \) LAW COMPAUNDER**

A compander consists of two blocks namely compressor and expander. These are used in communications systems to handle the required range of voltages to be transmitted from one point to another. In the \( \mu \) law compressor, the input voltage is transferred into output parameter, which in this case is the charge. The relation between input voltage, \( V_{in} \) and output(charge, \( z \)) is given by :

\[
z = \frac{K \ln(1 + \mu \frac{V_{in}}{V_{M}})}{\ln(1 + \mu)} \tag{7}
\]

where:

\( K \) is the maximum value of \( z \), 2e-8 Coulombs.

\( \mu \) is the parameter which governs the extent of compression, and is fixed to 50

\( V_M \) is the maximum input voltage, 10 Volts

This \( Q-V \) curve of figure(4) is then dissected into four regions and each region is approximated to a linear \( Q-V \) curve. From this, the various \( V_A \), \( V_B \) and the \( C_o \) are calculated for the
four capacitor-doublets, by the scheme described above. The parameters for each capacitor are obtained graphically from the figure(4) and are tabulated in table(1).

**TABLE I**  
Parameters of the QV curves

<table>
<thead>
<tr>
<th>$V_A$ (volts)</th>
<th>$V_B$ (volts)</th>
<th>Slope (coulomb/volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.1270</td>
<td>2.150e-8</td>
</tr>
<tr>
<td>0.1270</td>
<td>1.1569</td>
<td>6.3584e-09</td>
</tr>
<tr>
<td>1.1569</td>
<td>4.6514</td>
<td>1.8840e-09</td>
</tr>
<tr>
<td>4.6514</td>
<td>10</td>
<td>5.2500e-10</td>
</tr>
</tbody>
</table>

Knowing $V_A$ and $V_B$ for a doublet, $V_n$, the threshold voltage required in the n-MOS capacitor, is then calculated by the equation(4) and similarly, $V_p$, the threshold voltage required in p-MOS capacitor, can be calculated by the equation(5). $C_{max}$ for each capacitor is obtained, from the slope, by the relation

$$slope = C_{max}/2$$

It can be shown[2] that $V_n$ and $V_p$ are governed by $\phi_{mso}$, $Q_{FC}$, $\rho_1$ and $\phi_{mso}$, $Q_{FC}$, $\rho_1$ respectively. Keeping $\phi_{mso}$, $\phi_{mso}$ and $Q_{FC}$ as zero and assuming doping concentration for both p-MOS and n-MOS as $10^{17}$, bulk charge needed in the oxides have been calculated (assuming them to constant). The bulk charges depend on the required $V_n$ and $V_p$.

**Silicon dioxide** of constant thickness $200\mu$ is used, $C_{max}$ for each capacitor has been realized by taking the appropriate area for metal contact, which allows us to have constant oxide thickness! The physical constants of various MOS structures for each capacitor-doublet are given in table(2).

**TABLE II**  
Physical constants for the MOS structures

<table>
<thead>
<tr>
<th>Cross-section Area (cm$^2$)</th>
<th>Space Charge p-MOS (C/cc)</th>
<th>Space Charge n-MOS (C/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.479e-1</td>
<td>0</td>
<td>0.019483</td>
</tr>
<tr>
<td>6.9e-2</td>
<td>0.021897</td>
<td>0.088793</td>
</tr>
<tr>
<td>1.62e-2</td>
<td>0.02705</td>
<td>0.30124</td>
</tr>
<tr>
<td>1.365e-4</td>
<td>0.8019655</td>
<td>0.46018621</td>
</tr>
</tbody>
</table>

**V. WAVEFORM SHAPING**

Consider the circuit diagram shown in figure(5). It contains a non-linear capacitor in series with a passive load capacitor.

![Circuit diagram of harmonic generator.](image)

If a voltage $V_m$ of known waveform is applied at the input, then the input waveform can be transformed to any other waveform if the device provides a proper Q-V characteristic. This desired output voltage $V_o$ can be obtained either across the device or across the passive load capacitor depending on the Q-V characteristic that is provided by the device. The method of obtaining the required Q-V characteristics, and hence the nonlinear capacitor for the desired waveform transformation is discussed below.

**A. Calculation of Q-V characteristic**

In the circuit diagram shown in figure(5), the voltage drop across the device is given by,

$$V_{dev} = V_m - V_c,$$  \hspace{1cm} (8)
where \( V_m \) is the supply voltage and \( V_c \) is the voltage drop across the load capacitor. The Q-V relation of the device can be expressed as, \( Q_T = CV_c \), or,

\[
Q_T = C_L(V_m - V_{dcv}),
\]

(9)

where \( C_L \) is the capacitance of the load capacitor and \( Q_T \) be the terminal charge. If the output is taken across the load capacitor \( V_c \) will take the form of desired output. Similarly, if the output is taken across the device \( V_{dcv} \) can also be of the form of desired output when the conditions are appropriate. We realize the nonlinear device by the technique described previously in this paper, by the use of standard, uniformly doped MOS capacitor.

**B. Sinusoidal to triangular transform**

The expected output waveform \( V_o \) can be represented as

\[
V_o = K	heta
\]

(10)

for \( 0 \leq \theta \leq \frac{
\pi}{2} \), where \( K \) is the slope of the triangular wave, given by volts/rad. The terminal charge can now be written as

\[
Q_T = C_L(V_m - V_o)
\]

(11)

where \( V_m \) is the input sine wave given by \( V_m \sin \theta \) and the output is assumed to be taken across the device. The calculated Q-V characteristics, for this transformation for three different values of \( K \) are shown in figure(6). The input sinusoidal voltage amplitude, \( V_m \), is taken as 3 volts and the load capacitance, \( C_L \), as 20 \( \mu \)F. This nonlinear Q-V characteristic can then be realized by choosing appropriate capacitor-doublets, as described previously.

**VI. Conclusion**

A new method to synthesize a given non-linear capacitor using the standard, uniformly doped MOS capacitor is introduced in this paper. As an example, we have demonstrated various steps involved in designing of the capacitors for the case of \( \mu \)-law compander, and also those involved in transforming a given sinusoidal voltage waveform into a triangular waveform, specifically. Values of the parameters of various capacitors required for the \( \mu \)-law compander suggests its practical feasibility and thus it can be made easily using the current CMOS technology. Also the power dissipation in this circuit is almost negligible due to the use of only capacitive elements. Hence, this approach has a potential for developing low power circuits.

**VII. Acknowledgement**

The authors would like to thank Prof. J. Vasi, IIT Bombay and Prof. M. Satyam, IISc Bangalore, for drawing attention to several important aspects and their valuable guidance. One of the authors (Siddhartha) thanks Jawaharlal Nehru Centre of Advanced Scientific Research (India) for their financial support through a visiting fellowship at the Indian Institute of Science, Bangalore, India, where the major part of this work was done.

**VIII. References**

2. Sze, S.M., “Physics of Semiconductor devices”.
5. Detailed derivation of breakpoints in the QV curve for the series combination using the Poisson’s equation, 
http://www.ee.iitb.ac.in/ palkesh/appendix.ps