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 μ-law compander is attempted at. Also, as an application in wavefrom 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[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[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[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 p-MOS and n-MOS capacitors. Physical parameters of the MOS capacitors required for designing a μ-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_o. By connecting these devices in parallel we get a non-linear capacitor with piecewise linear parts. This is shown in figure(2).

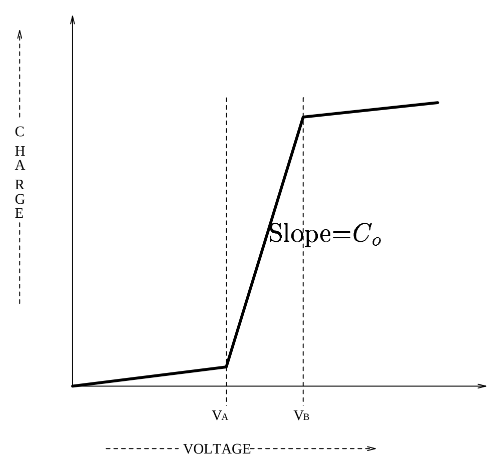

Fig. 1. Typical Q-V Characteristics

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.

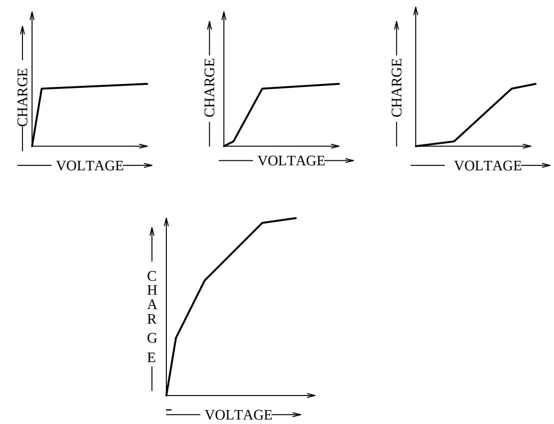

Fig. 2. Parallel combination of capacitors

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 combonation,

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

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 **capacitor-doublet.**

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

$$V_A = V_n \tag{4}$$

$$V_B = V_n + 2V_p \tag{5}$$

$$C_\circ = C_{max}/2 \tag{6}$$

where, V_n and V_p are the points at which the change in slope is assumed to occur in the p and

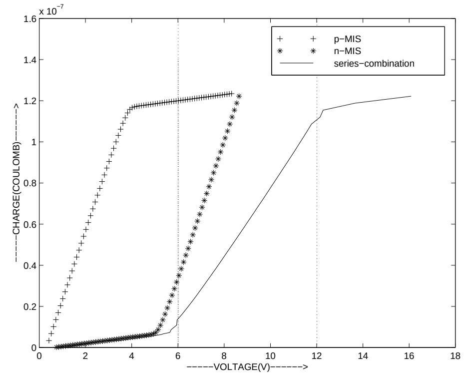

Fig. 3. Typical variation of Q vs V of a series combination of n-MOS and p-MOS capacitors. (Doping concentration as $\mathbf{10^{17}}$ and t_{ox} = $\mathbf{100^\circ A}$)

n characteristics, and are essentially the threshold voltages[2], and hence, just by controlling the physical parameters like ϕ_{ms} and the bulk charge, we can get doublets with different values of V_A and V_B. $C_\circ$ 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 μ-law compander

IV. Design of Nonlinear Capacitor Bank for a μ law compander

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 μ 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.
μ	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 $C_\circ$ are calculated for the

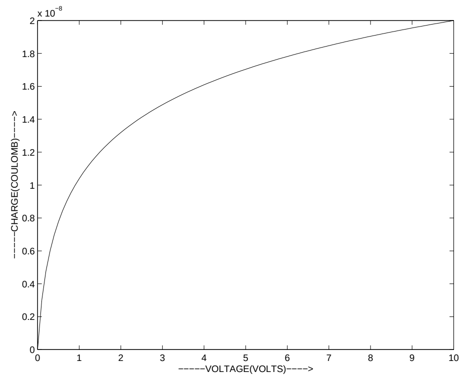

Fig. 4. QV characteristic of the non-linear capacitor for μ-Law Compander

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

V_A(volts)	V_B(volts)	Slope(coulomb/volts)
0	0.1270	2.150e-8
0.1270	1.1569	6.3584e-09
1.1569	4.6514	1.8840e-09
4.6514	10	5.2500e-10

Knowing V_A and V_B for a doublet, V_n, the thershold 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 ϕ_{msn}, Q_{FC}, ρ_i and ϕ_{msp}, Q_{FC}, ρ_i respectively. Keeping ϕ_{msp}, ϕ_{msn} and Q_{FC} as **zero** and assuming doping concentration for both p-MOS and n-MOS as $\mathbf{10^{17}}$, 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°A** 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

Cross-section Area (cm^2)	Space Charge p-MOS (C/cc)	Space Charge n-MOS (C/cc)
2.479e-1	0	0.019483
6.9e-2	0.021897	0.088793
1.62e-2	0.02705	0.30124
1.365e-4	0.8019655	0.46018621

V. Waveform Shaping

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

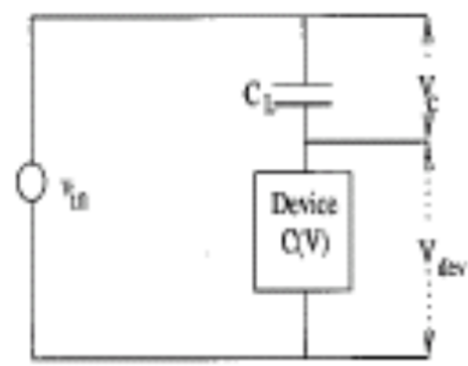

Fig. 5. Circuit diagram of harmonic generator.

If a voltage V_{in} 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,

$$V_{dev} = V_{in} - V_c, \tag{8}$$

where V_{in} 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,

$$Q_T = C_L(V_{in} - V_{dev}), \tag{9}$$

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_{dev} 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

$$V_o = K\theta \tag{10}$$

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

$$Q_T = C_L(V_{in} - V_o) \tag{11}$$

where V_{in} 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 fF. This nonlinear Q-V characterstic 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 μ-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 μ-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.

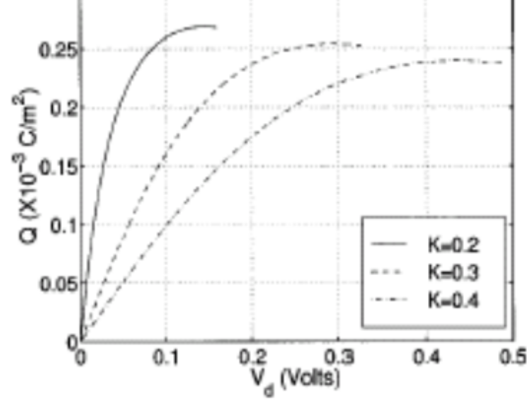

Fig. 6. The required Q-V characteristics for sinusoidal to triangular voltage waveform transformer for different values of K. C_L = 20 fF, A=200 μm^2 and V_m = 3 volts.

VII. Acknowledgement

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