Influence of the MOS varactor gate doping on the performance of a 2.7GHz - 4GHz LC-VCO in standard digital 0.12µm CMOS technology

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Abstract

The influence of the gate type of the MOS varactor on the tuning range and phase noise of a fully integrated LC-VCO (voltage controlled oscillator) is presented. Three varactors in multifinger layout with STI (shallow trench isolation) are compared. The polysilicon gate is either entirely n- or p-doped or the fingers have alternating n- or p- doping. Differences in capacitance, steepness and quality factor are shown.

Two identical VCOs with the varactors having n-gates or np-gates are measured. Homogenous doping increases the VCO tuning range to 1.31GHz (∓19.6%) in comparison to 1.06GHz (∓14.8%) obtained by mixed doping. Mixed doping however has the advantages of linearized frequency behaviour, lower upconverted flicker noise and reduced maximum sensitivity to variations in supply voltage.

With a current consumption of only 1mA from a supply voltage of 1.5V both VCOs show a phase noise of -115dBc/Hz and a figure of merit (FOM) of -183.3dBc/Hz at a 1MHz offset from a 4GHz carrier.

1. Introduction

Varactors with large capacitance tuning ranges $C_{max}/C_{min}$ allow the use of large inductances and reduction of power consumption [1] in the VCO. Also process variations leading to capacitance variations up to 20% can be more easily compensated.

This paper documents the influence of the gate doping on a MOS varactor with high capacitance tuning range. It considers capacitance, capacitance steepness and quality factors. The resulting differences in tuning and phase noise performance of fully integrated VCOs in standard digital 0.12µm CMOS technology are investigated.

2. Design

The varactors are of accumulation type in $n^-$-well. STIs (Shallow Trench Isolations) reduce parasitic capacitances [2]. Small, grounded p-regions prevent inversion and increase tuning range by enabling deep depletion. Cross-sections of all varactors with different gate doping are shown in Fig. 1. Tuning voltages $V_{tune}$ are applied to the $n^+$-regions in $n^-$-well and the VCO signal appears at the gates.

![Cross sections of the three varactors with different gate doping.](image)

Fig. 1. Cross sections of the three varactors with different gate doping.

Fig. 2 shows the topology of the fully integrated, symmetric VCO [1].

![VCO topology](image)

Figure 2. VCO topology

The differential, symmetrical inductor utilizes metals 4,5,6 (copper) of the six metal layer process in parallel. The staggered winding width with a 25% increase from winding to winding reduces the series resistance.

3. Measurement results

Three varactors with different gate doping are realized in identical multifinger layout. The gate length (distance of the STIs) is 0.32µm.

Two identical, fully integrated VCOs differing only in the varactor (n or np), have been manufactured in standard 0.12µm CMOS technology. They consume 1mA from a 1.5V supply voltage.
Fig. 3 shows a die photo of one VCO. Die and inductor size are 450μm x 1mm and 190μm x 190μm, respectively.

Figure 3. Die photograph of one VCO. Fill structures are suppressed in the area of the inductor and the VCO-core.

The varactors and the inductor were separately characterized by S-parameter measurements (HP8510). Values for the varactor’s $C$ and $Q$ are retrieved by

$$
C = -\frac{1}{2\pi f \text{Im} \left( \frac{1}{Y_{11}} \right)} \tag{1}
$$

$$
Q = -\frac{1}{2\pi f \text{Re} \left( \frac{1}{Y_{11}} \right)}
$$

with $R_s$ the series resistance of the varactor.

The inductor features an inductance of 4.5nH and a DC series resistance of 4.7Ω. The quality factor according to bandwidth definition [3] is between 11.6 and 14.8 with higher quality factors at higher frequencies.

Phase noise was measured with a Eurotest PN9000 (delay line method).

### 3.1. Tuning

Fig. 4 compares the capacitance behaviour of the three varactors. Differences are readily explained by the shift in flat-band voltage introduced by the different gate doping.

- For $n$-gates the flat-band voltage is low (close to 0V), but is shifted by ca. 1V when using $p$-doping for the gate.
- The varactor with mixed gate doping (50% $n$, 50% $p$) resembles the behaviour of two parallel varactors with half the gate width but different gate doping.
- At zero tuning voltage all varactors reach accumulation and the gate oxide and the parasitic capacitances determine their maximum capacitance. At the maximum tuning voltage of 1.5V all varactors remain in depletion for a wide range of gate voltages. Only close to $V_{gate} = 1.5V$ the capacitance of the varactors with $n$- and $p$-doped varactors increases at the onset of accumulation.

To realistically predict frequency tuning ranges of the VCO averaged capacitance tuning ranges $C_{av,\text{ratio}}$ provide more insight than the absolute values $C_{\text{ratio}}$ [2]. Fig. 5(left) summarizes the results for both figures. The varactor with $p$-gates reaches the highest absolute value of 5.5, as it remains in deep depletion throughout the whole gate voltage range and therefore has a very low minimum capacitance. However, the averaged value $C_{av,\text{ratio}} = 2.4$ is considerably lower, as the averaging process strongly reduces the maximum averaged capacitance value compared to the absolute $C_{\text{max}}$. The varactor with $n$-gates suffers less from averaging and the absolute tuning range of 4.7 is only reduced to 3.1 after averaging. The varactor with mixed gate doping reaches values between the two other devices.

![Figure 4. Measured capacitance of the varactors with different gate doping for $V_{tune} = 0V$, 1.5V @ 2GHz.](image)

![Figure 5. Measured absolute and averaged varactor capacitance tuning ranges ($f = 2$GHz) and absolute VCO frequencies.](image)

Fig. 5(right) summarizes the absolute oscillation frequencies of both VCOs. With a $n$-doped varactor the VCO offers a tuning of 1.31GHz ($\pm19.6\%$), with mixed doping 1.06GHz ($\pm14.8\%$) is reached. Lower averaged capacitance values with $np$-gates shift the oscillation frequencies of the VCO to higher values.

The normalized frequencies of the two VCOs (Fig. 6) reveal a lower frequency tuning range but more linear behaviour for the mixed gate doping. The lower $f_{max}/f_{min}$ value is a direct consequence of the lower averaged capacitance tuning range of the varactor with $np$-gates. The more linear behaviour, which eases PLL-design, results from the flatter and therefore smoother capacitance behaviour of the varactor.

Simultaneously the mixed doping reduces the maximum sensitivity to variations in supply voltage ($K_{vdd,max}$) by 20% from 800MHz/V with $n$-gates to 600MHz/V.
3.2. Phase noise

As the varactor’s quality factor can have an influence on the phase noise the absolute and averaged quality factors of the varactors need to be considered (Table 1). Similarly to the capacitance the absolute quality factors are more meaningful, due to the large VCO signal swing at the gate. The $Q_{\text{min}}$ value (at $V_{\text{tune}} = 0$) of all varactors is equal, as it occurs for all in accumulation with comparable capacitances and equal resistances which are determined by the path through the $n^-$-well.

Table 1. Measured absolute and averaged small-signal quality factors.

<table>
<thead>
<tr>
<th>$V_{\text{tune}}$</th>
<th>$n$</th>
<th>$p$</th>
<th>$np$</th>
<th>$n$</th>
<th>$p$</th>
<th>$np$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0V</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>21</td>
<td>74</td>
<td>26</td>
</tr>
<tr>
<td>0.5V</td>
<td>19</td>
<td>37</td>
<td>24</td>
<td>37</td>
<td>$&gt;200$</td>
<td>76</td>
</tr>
<tr>
<td>1V</td>
<td>19</td>
<td>69</td>
<td>29</td>
<td>72</td>
<td>$&gt;200$</td>
<td>$&gt;200$</td>
</tr>
<tr>
<td>1.5V</td>
<td>33</td>
<td>140</td>
<td>46</td>
<td>$&gt;200$</td>
<td>$&gt;200$</td>
<td>$&gt;200$</td>
</tr>
</tbody>
</table>

The shift in flat-band voltage for $p$-gates or the flatter capacitance characteristic for mixed doping explains differences in minimum averaged quality factors (at $V_{\text{tune}} = 0$V). The varactor with $p$-gates is in depletion for a wide range of gate voltages with a small capacitance and simultaneously a low resistance (shorter path through well) resulting in high absolute quality factors. Contrarily the $n$-doped varactor is for almost all gate voltages in accumulation with simultaneously high capacitance and resistance. Therefore the averaged quality factor differs little from the absolute value. Again the varactor with mixed gate doping reaches values between the other two devices. Above $V_{\text{tune}} = 0.5V$ the averaged quality factors are all well above 35. The quality factor of the inductor is always considerably lower, and it is expected that mainly the inductor determines the phase noise of the VCO (especially at high tuning voltages /frequencies).

Phase noise will be compared for both VCOs at the same frequency

$$f \propto \frac{1}{\sqrt{C_{av}(V_{\text{tune}})} + C_p}$$

with $C_p$ the parasitic capacitances in the rest of the VCO (inductor, wiring, ...). For the same carrier frequency the varactors need to have the same averaged capacitance. From the values in table 2 it becomes clear that for the same frequency (averaged capacitance) the tuning voltage for the $n$-doped varactor is higher.

Table 2. Measured averaged capacitances, absolute capacitance variations and maximum capacitance slopes of the varactors used in the VCOs.

<table>
<thead>
<tr>
<th>$V_{\text{tune}}$</th>
<th>$C_{av}/pF$</th>
<th>$\Delta C/pF$</th>
<th>max. $\frac{dC}{dV_{\text{tune}}}/pF$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0V</td>
<td>1.15</td>
<td>0.86</td>
<td>0.66</td>
</tr>
<tr>
<td>0.5V</td>
<td>0.89</td>
<td>0.56</td>
<td>0.64</td>
</tr>
<tr>
<td>1V</td>
<td>0.61</td>
<td>0.43</td>
<td>0.86</td>
</tr>
<tr>
<td>1.5V</td>
<td>0.38</td>
<td>0.30</td>
<td>0.53</td>
</tr>
</tbody>
</table>

The variation of capacitance over gate voltage results in harmonic distortion and upconverted flicker noise, which is most present at low offset frequencies. The influence of two parameters are taken into account: the maximum slope $dC/dV_{\text{gate}}$ and the absolute capacitance variation with gate voltage $\Delta C(V_{\text{tune}})$, which is an integral of the slope.

Mixed doping halves the maximum slope of the capacitance compared to the $n$-gate varactor which is a result of the smoother two-transition behaviour. At low tuning voltages the variations $\Delta C(V_{\text{tune}})$ are lower with $n$-poly as the varactor remains in accumulation for a wide range of gate voltages (flat-band close to 0V). Above 0.5V however, the $np$-varactor features the lower capacitance variations, due to its $p$-half which is in depletion for all gate voltages. At a given VCO frequency (given $C_{av}$) the capacitance variation $\Delta C$ as well as the maximum slope $dC/dV_{\text{gate}}$ are lower for mixed doping. Therefore it is expected that the close-in phase noise of the VCO with the mixed gate doping varactor is always lower.

Figs. 7 - 9 show the measured phase noise for frequencies between 3 GHz and 4 GHz. At 3.06GHz (Fig. 7) the VCO with mixed doping varactor features significantly lower phase noise throughout the entire offset frequency range. This is astonishing, as the minimum averaged quality factor is lower with $np$-doping due to the lower tuning voltage. The nevertheless lower phase noise is explained by the more symmetric waveform that has a large effect on the phase noise [4]. Only well above 5MHz offset the results for both VCOs converge, indicating a very wide $1/f^2$ region with the $n$-varactor. Less harmonic distortion due to smaller capacitance variation with mixed doping outweighs the quality factor advantage of the $n$-varactor.
VCOs is less pronounced. Although the difference in 3.67GHz (Fig. 8), but, the difference between the two parasitic capacitances averaged capacitance is much lower. With constant parameters have less influence. This is obvious, as the results for both VCOs converge close to 5MHz, indicating a less harmonic distortion for the n-varactor VCO as at 3.06GHz.

At high frequencies the gate type does not play a role (Fig. 9): both VCOs reach the same phase noise. The averaged quality factors are high enough to not have any influence. Simultaneously the averaged capacitance is so low compared to the total capacitance $C_{av} + C_{p}$, that differences in capacitance variations $\Delta C(V_{tune})$ are not effective any more.

The VCO with mixed doping varactor reaches the same phase noise for all carrier frequencies, indicating low harmonic distortions at all VCO frequencies.

4. Conclusion

The influence of the gate type of the MOS varactor on the tuning range and phase noise of a fully integrated LC-VCO (voltage controlled oscillator) is presented. Three varactors with different gate doping n, p or mixed np are compared. Mixed doping results in smoother capacitance and resistance behaviour with two depletion-accumulation transitions. Quality factors and tuning ranges are always between the values of the entirely n- or p-doped devices, with the lowest quality factor but highest tuning range for n-doping.

The devices with n-gates or mixed doping are tested in otherwise identical VCOs. The higher tuning range of the n-varactor increases the VCO tuning range from 1.06GHz ($\pm 14.8\%$) with mixed doping to 1.31GHz ($\pm 19.6\%$). The np-gates offer several significant advantages due to the smoother capacitance characteristic. The upconverted flicker noise (especially at low carrier frequencies) is significantly lower with mixed doping. Capacitance variations with gate voltage leading to harmonic distortions outweigh the influence of the quality factor. The np-gates lead further to highly linear frequency behaviour of the VCO due to the smoother capacitance characteristic of the varactor. This also results in a reduction of the maximum sensitivity to variations in supply voltage ($K_{vdd,max}$) by 20%.


