An analysis on lower bounds of supply voltages for enhanced-swing Colpitts oscillators

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Introduction Energy harvesting (EH) converts low energy obtained from the surrounding environment into electric power. Since the energy obtained from EH largely varies depending on the environmental conditions, an integrated circuit operating at an extremely low voltage is desired. In [1], Enhanced-Swing Colpitts Oscillator (ESCO) (Fig. 1) that can oscillate at a low voltage is discussed. However, the theoretical limit of the minimum power supply voltage $V_{dd}(min)$ has not been clarified since the theoretical value of $V_{dd}(min)$ was 8.2 mV while the measured value was 86 mV [1]. Therefore, in this research we focus on the theoretical lower bound of the power supply voltage for ESCO.

Theoretical limit of operating voltage G_1 and G_2 are the conductances associated with the parasitic resistances of the inductors L_1 and L_2, respectively. v_s and v_d are the amplitudes of the source and the drain of the transistor, respectively, as shown in Fig. 2. The loss G_L of the whole circuit is expressed as (1), where a is a voltage gain of v_d/v_s [1]. In order for ESCO to maintain oscillation, it is necessary for the transistor to compensate for the power loss due to G_L. Therefore, $V_{dd}(min)$ is determined under the condition that the effective conductance $g_m - ag_{md}$ of the transistor at $v_{gs} = v_{ds} = V_{dd}$ is larger than G_L (v_{gs}: gate-source voltage, v_{ds}: drain-source voltage). In [1], the transconductance of (2) is used assuming that the transistor operates in the subthreshold region, where V_T is a thermal voltage, and V_{th} is a threshold voltage, I_0 is the drain current when $v_{gs} = V_{th}$ and $v_{ds} \gg V_T$, and k is expressed by $1/(SV_T)$ using the subthreshold coefficient S. In this research, g_m and g_{md} are defined as (3) and (4), respectively, based on the EKV model [2] that can cover wide operation regions from the strongly inverted region to the subthreshold region.

$V_{dd}(min)$ can be obtained by (5), where ${g_m}^{V_{dd}(min)}$ and ${g_{md}}^{V_{dd}(min)}$ are g_m and g_{md} at $v_{gs} = v_{ds} = V_{dd}(min)$.

Verification SPICE simulation was done for verification. ROHM 0.18 μm 1.8 V transistor model was used. In order to lower the operation voltage, the threshold voltage was lowered. We assumed that the SPICE parameter *Vth0* can be changed by adjustment of channel implantation. Fig. 2 shows a SPICE simulation waveform when V_{dd} = 0.1 V. The parameters for the passive elements are after [1]. Fig. 3 compares $V_{dd}(min)$ of the previous model (2) [1], the proposed model (5) and SPICE simulation results. $V_{dd}(min)$ of SPICE simulation was defined so as to satisfy $v_s \geq V_{dd}$. The proposed model is in good agreement with SPICE simulation results for a wide *Vth0* range while the previous model has no *Vth0* dependence. (5) suggests that g_m (g_{md}) mainly determines $V_{dd}(min)$ for higher (lower) *Vth0*. The error between the simulation value and the theoretical value was reduced from 44 mV to 3 mV.

Summary The proposed model well matches $V_{dd}(min)$ in a wide *Vth0* range with SPICE results. Oscillation at $V_{dd}(min)$ of about 50 mV is expected with a threshold voltage of around -30 mV at 20°C. We will also present temperature dependence of $V_{dd}(min)$ at the conference.

References

[1] M.B.Machado et al., IEEE TCAS-I, vol. 61, no. 2, pp. 347-357, Feb. 2014.

[2] C.C.Enz et al., AICSP, vol. 8, pp. 83-114, 1995.

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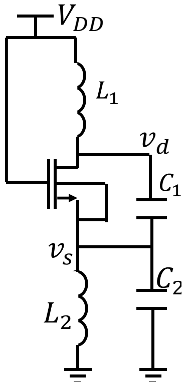


Fig. 1. ESCO

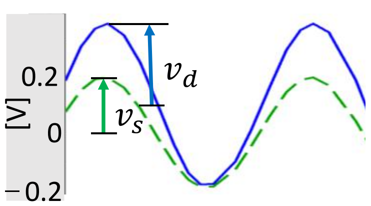
$$G_L = (a^2 G_1 + G_2)/(a-1) \qquad (1)$$

$$g_m = I_0 e^{\frac{v_{gs}-V_{th}}{kV_T}} / (kV_T) \qquad (2)$$

$$g_{\mathrm{m}}(v_{gs}, v_{ds}) = I_0 \left[\ln\left(1 + e^{\frac{v_{gs}-V_{th}}{2kV_T}}\right)\right] e^{\frac{v_{gs}-V_{th}}{2kV_T}} \left(1 - e^{\frac{-v_{ds}}{kV_T}}\right) \Big/ \left[kV_T\left(1 + e^{\frac{v_{gs}-V_{th}}{2kV_T}}\right)\right] \qquad (3)$$

$$g_{\mathrm{md}}(v_{gs}, v_{ds}) = I_0 \left[\ln\left(1 + e^{\frac{v_{gs}-V_{th}}{2kV_T}}\right)\right]^2 e^{\frac{-v_{ds}}{kV_T}} \Big/ (kV_T) \qquad (4)$$

$${g_m}^{V_{dd}(min)} - a{g_{md}}^{V_{dd}(min)} = G_L \qquad (5)$$



$V_{dd} = 0.1$[V], Temp = 20℃
$Vth0 = 0$[V], $L_1 = 13$[nH]
$L_2 = 24$[nH], $C_1 = 6$[pF]
$C_2 = 4$[pF], $f = 935$[MHz]
$G_1 = 605$[μS], $G_2 = 355$[μS]

Fig. 2. ESCO oscillation waveform at $V_{dd} = 0.1$ V

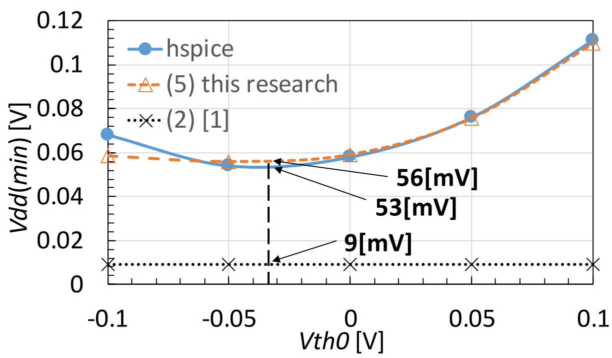


Fig. 3. *Vth0* dependency of $V_{dd}(min)$