A 220nA 32-kHz Crystal Oscillator with wide Voltage Range (1.0 - 5.5 V) for Battery-Operated MCUs

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1. Introduction
This paper describes a low-power (220 nA) 32-kHz crystal oscillator operating over a wide voltage range (1.0 - 5.5 V) with a sufficient oscillation margin (10 times).

Most MCUs have a watch (RTC: real-time clock) function using a 32-kHz crystal oscillator, which is the only way to achieve an accuracy of 30 seconds/month (10-ppm error). Since the oscillator operates even in standby mode, its operation current should be minimized. Also it's necessary to operate at low voltage for the battery operation, while maintaining the compatibility with the legacy voltage (3.0 - 5.0 V).

Fig. 1(a) shows a conventional CMOS inverter type oscillator. [1] Since the oscillation power is proportional to the square of voltage, it is not suitable for low power. Using the regulator circuit for supplying a constant voltage is a general improvement method. However it yields extra current consumption and area increase. Fig. 1(b) shows a constant-current type oscillator [2][3][4]. Although it can operate over a wide voltage range, its temperature stability is poor because $g_m$ of $M_1$ decreases at high temperature.

2. Low-power circuit design
Fig. 2 shows our proposed circuit. The two improvements towards low-current operation are PTAT (proportional to absolute temperature) bias current for the oscillator and an adaptive reference voltage for the comparator.

2.1 An oscillator with PTAT bias current
An effective way for low-power design is reducing the bias current $I_D$, which is a major part of the operating current of the oscillator. However, reducing $I_D$ decreases the oscillation margin as described below. The oscillation margin is defined as the negative resistance $R_N$ divided by the crystal's equivalent series resistance ($R_e$: about 60 kΩ). $R_N$ can be measured by inserting a limiting resistance and observing the oscillation as shown in Fig. 1. By impedance analysis of the circuit, we obtain $R_N$ as follows.

$$ R_N = -\frac{g_m}{\omega^2 C_s C_D} = -\frac{g_m}{(2\pi f_C)^2} = -\frac{q I_D}{n kT(2\pi f_C)^2} \tag{1} $$

since $g_m = q I_D / n kT$ ($M_1$ is in subthreshold region) and $C_s = C_D$ ($q$: elementary charge, $k$: Boltzmann constant, $T$: temperature, $n$: subthreshold-slope factor, $\omega$: oscillation angular frequency). The crystal's load capacitance $C_L$ is expressed as $C_L = C_s C_{inv}(C_D + C_s)$, where $C_{inv}$ and $C_D$ are the capacitances shown in Fig. 1. Thus, reducing $I_D$ yields a smaller $R_N$.

Eq. (1) also indicates that a constant-current type circuit has a smaller oscillation margin at higher temperature because $R_N \propto 1/T$.

To ensure a sufficient margin at a high temperature an extra current is needed at a low temperature. From the above consideration, $I_D$ is designed to be not constant but proportional to absolute temperature (PTAT), and the PTAT current supply circuit with a wide voltage range shown in Fig. 2 is used to keep at least 10-times oscillation margin ($R_N > 600$ kΩ) at any temperature.

2.2 A comparator with adaptive reference voltage
One of the issues of the common-source type oscillator circuit is the design of the comparator. The oscillator output signal XOUT is as small as 150 - 350 mVpp and its level is dependent on the $V_{th}$ of $M_1$, which is affected by process and temperature variations. In addition, the center voltage of XOUT goes low from its DC level as the oscillation amplitude grows as shown in Fig. 3(a). This is because of the non-linear (exponential) characteristics of $M_1$ operating in the subthreshold region. The current of $M_1$, $I_D$, is proportional to the exponential of $XIN$, while the average of $I_D$ is equal to $I_{Q1}$, as shown in Fig. 3(b). Therefore the center of $XIN$ must be lower than its DC level. The center of XOUT also goes low through $R_F$. If the reference voltage $V_{REF}$ for the comparator is not adjusted, the duty cycle of the output signal XC will be poor. In the worst case, the comparator will fail to detect the signal.

The adaptive reference voltage generator is designed to solve this problem. An nMOSFET $M_2$ with the same structure as $M_1$ is used to generate $V_{REF}$ that follows fluctuations in $V_{th}$. In addition, the current density of $M_2$ is set to 1/10.5 that of $M_1$ by adjusting the current-mirror and channel-width ratios to cope with the center-voltage lowering.

3. Results of measurement
The oscillator circuit was implemented in an MCU fabricated with a 130-nm CMOS process as shown in Fig. 4. The circuit takes up 200 x 250 µm². The quartz crystal with the world's smallest $C_L$ (3.1 pF; SSP-T7-FL from Seiko Instruments Inc.) was used in evaluation. The operation current was only 220 nA at 3.0 V, 25°C.

The evaluation results for $I_D$ and $R_N$ are shown in Fig. 5. The PTAT characteristic of $I_D$ keeps $R_N$ almost constant against variations in supply voltage (a) and temperature (b). Moreover, the measured results are close to the simulation results. As a result, a sufficient oscillation margin (10 times) is ensured even under the worst conditions. The evaluation results for duty cycle against the supply voltage and nMOSFET's $V_{th}$ are shown in Figs. 6(a) and (b), respectively. The adaptive reference voltage keeps the duty cycle almost constant.

The characteristics of this circuit are summarized in Table 1. The circuit is expected to realize the smallest MCU standby current 420 nA.

4. Conclusion
A 220-nA 32-kHz crystal-oscillator circuit has been designed and evaluated. It can operate at 1.0 - 5.5 V while an oscillation margin of 10 times is maintained even under worst conditions. Using an nMOSFET common-source circuit with PTAT supply current provides an almost constant oscillation margin over wide voltage and temperature ranges. The comparator using an adaptive reference voltage can detect a small and process- and temperature-dependent oscillation signal. The circuit was applied in an MCU for extended battery life.
5. Acknowledgments
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References

Fig. 1 Conventional crystal oscillator circuits
(a) CMOS Inverter type  (b) Constant current type

Fig. 2 Proposed crystal oscillator circuit
PTAT bias generator       Adaptive comparator

Fig. 3 Oscillation waveforms
(a) Center-voltage lowering     (b) Current waveform

Fig. 4 Chip micrographs
Fig. 5 Bias current (I_D) and negative resistance
(a) Voltage dependence  (b) Temperature dependence

Fig. 6 Measured results for duty cycle
(a) Voltage dependence  (b) Process dependence

Table.1 Comparison of crystal oscillator circuits

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<td>1.0mA @1.8V</td>
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*32-kHz oscillator + RTC