US009438165B2

(12) **United States Patent**
Powell et al.

(10) **Patent No.: US 9,438,165 B2**
(45) **Date of Patent: Sep. 6, 2016**

(54) **RC OSCILLATOR**

(71) Applicant: **Silicon Laboratories Inc.**, Austin, TX (US)

(72) Inventors: **Matthew R. Powell**, Austin, TX (US); **Axel Thomsen**, Austin, TX (US); **Nicholas M. Atkinson**, Austin, TX (US)

(73) Assignee: **Silicon Laboratories Inc.**, Austin, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/509,754**

(22) Filed: **Oct. 8, 2014**

(65) **Prior Publication Data**

US 2016/0105148 A1 Apr. 14, 2016

(51) **Int. Cl.**

H03K 3/26	(2006.01)
H03B 5/24	(2006.01)
H03K 3/011	(2006.01)
H03K 3/0231	(2006.01)

(52) **U.S. Cl.**

CPC ***H03B 5/24*** (2013.01); ***H03K 3/011*** (2013.01); ***H03K 3/0231*** (2013.01)

(58) **Field of Classification Search**

CPC H03K 3/0231; H03K 3/011; H03K 3/354; H03K 4/502; H03K 3/03; H03K 4/501; H03K 3/012; H03L 1/022; H03L 1/00; H03L 7/00; H03L 7/02; H03L 1/026; H03L 7/097; H03L 1/02; H03L 7/0891; H03L 7/0995; H03L 7/181; H03B 5/24

USPC 331/111, 143; 327/298, 131, 136, 132

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,157,265	A *	12/2000	Hanjani	H03K 3/0231 327/298
2008/0290955	A1*	11/2008	Fort	H03K 3/011 331/57
2010/0013566	A1*	1/2010	Kim	H03K 4/502 331/111

* cited by examiner

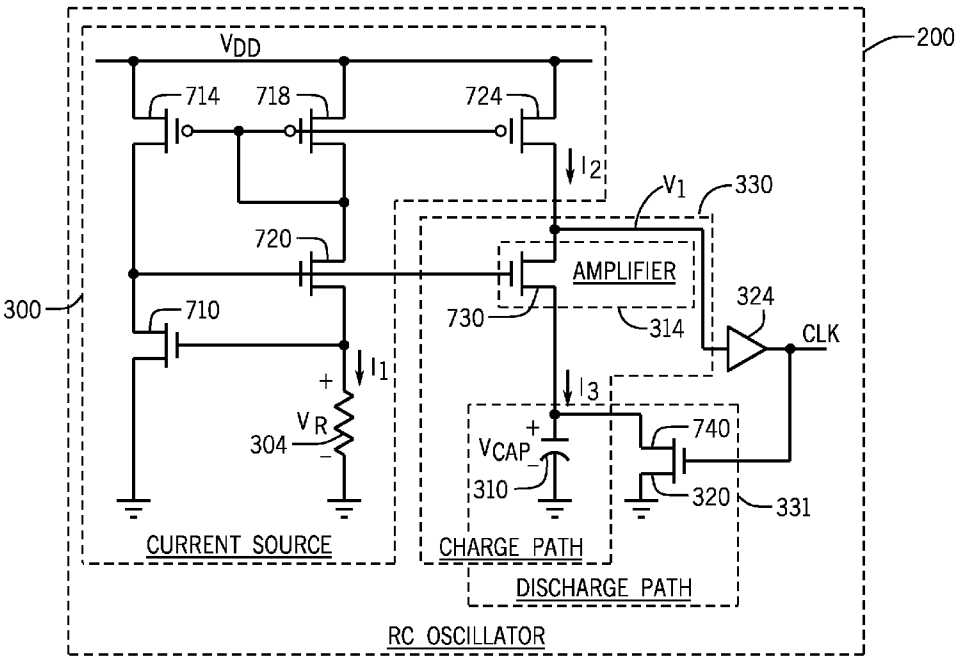
Primary Examiner — Arnold Kinkead

(74) *Attorney, Agent, or Firm* — Trop Pruner & Hu, P.C.

(57) **ABSTRACT**

A method includes using a current source to provide a charging current to a capacitor of a resistor-capacitor (RC) tank of an RC oscillator. The method includes using a resistor of the current source as a resistor for the RC tank.

14 Claims, 5 Drawing Sheets



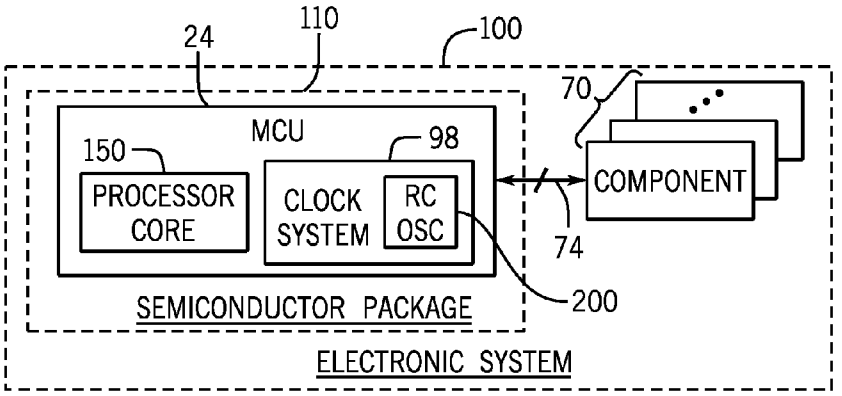

24
110
100
70
MCU
98
150
PROCESSOR CORE
CLOCK SYSTEM
RC OSC
COMPONENT
74
200
SEMICONDUCTOR PACKAGE
ELECTRONIC SYSTEM

FIG. 1

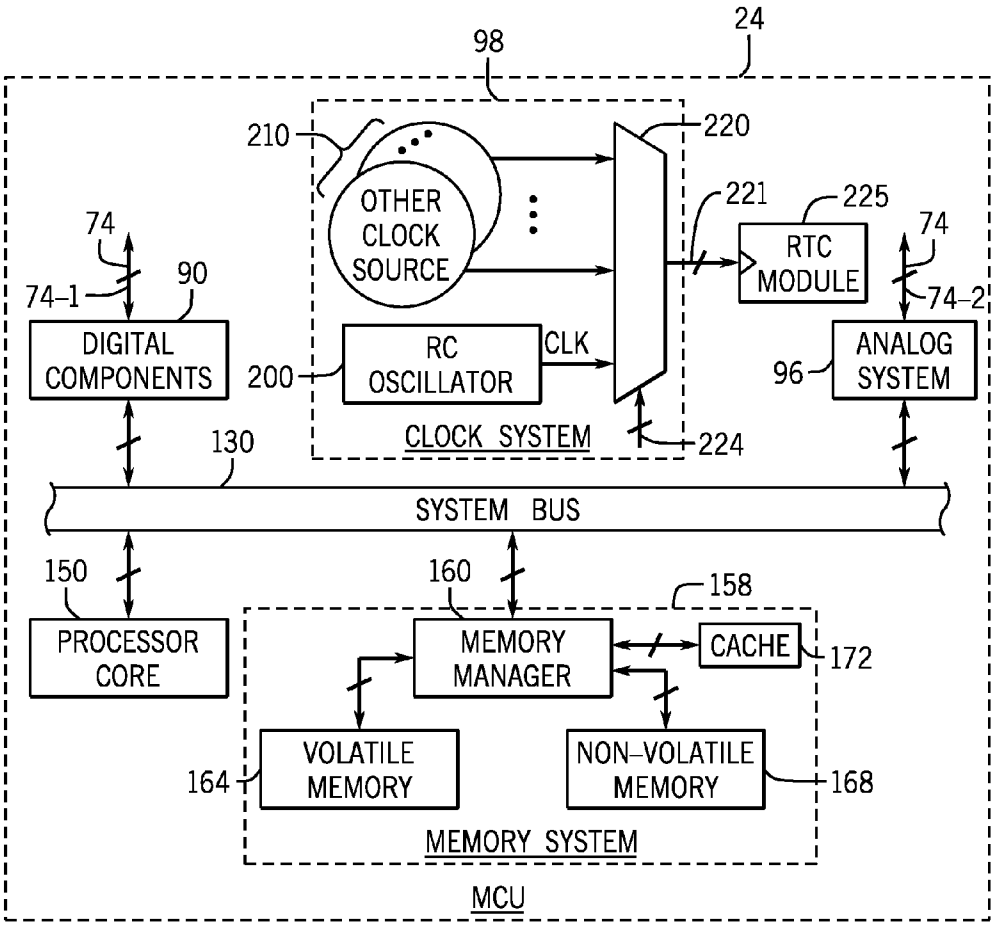

98
24
210
220
OTHER CLOCK SOURCE
221
225
74
RTC MODULE
74
74–1
90
74–2
DIGITAL COMPONENTS
200
RC OSCILLATOR
CLK
96
ANALOG SYSTEM
CLOCK SYSTEM
224
130
SYSTEM BUS
150
160
158
PROCESSOR CORE
MEMORY MANAGER
CACHE
172
VOLATILE MEMORY
164
NON–VOLATILE MEMORY
168
MEMORY SYSTEM
MCU

FIG. 2

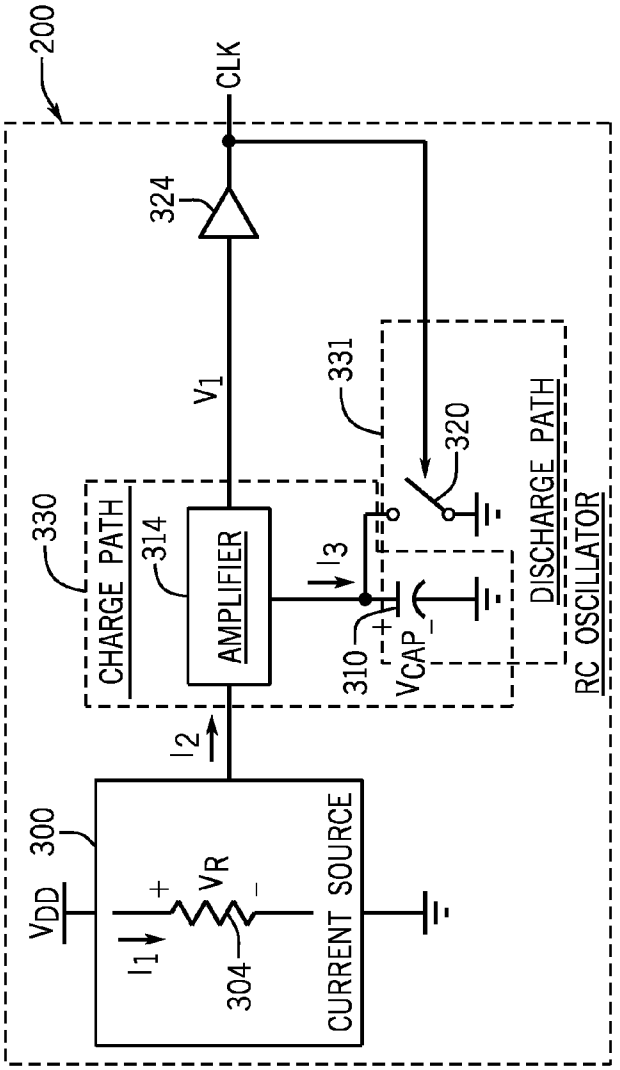

200
CLK
324
V1
331
320
330
CHARGE PATH
314
AMPLIFIER
I3
310
VCAP
DISCHARGE PATH
RC OSCILLATOR
I2
300
VDD
VR
I1
304
CURRENT SOURCE

FIG. 3

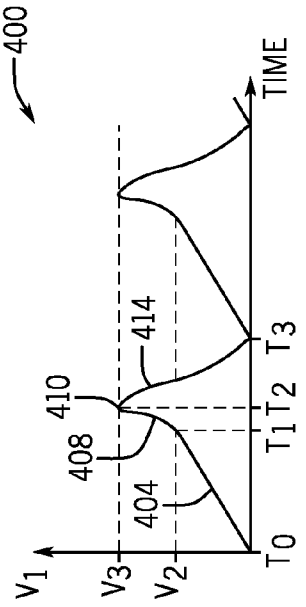

400
TIME
414
410
408
404
T0
T1
T2
T3
V1
V3
V2

FIG. 4

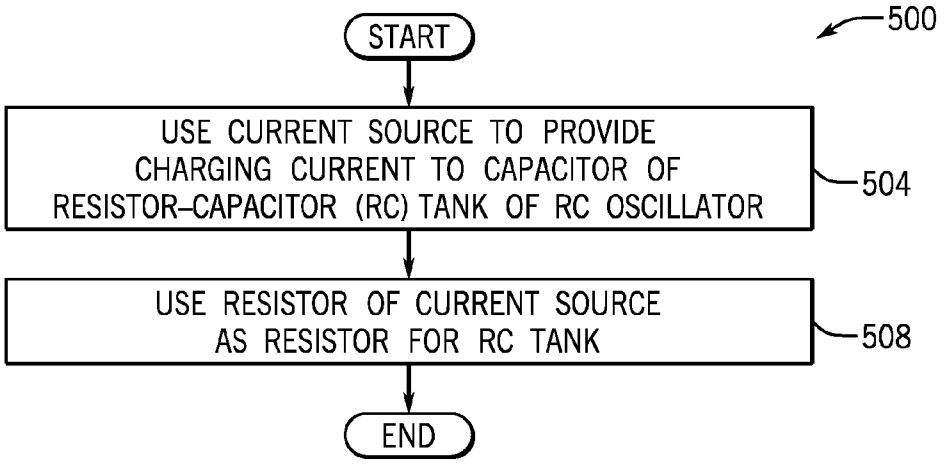

500
START
USE CURRENT SOURCE TO PROVIDE CHARGING CURRENT TO CAPACITOR OF RESISTOR–CAPACITOR (RC) TANK OF RC OSCILLATOR
504
USE RESISTOR OF CURRENT SOURCE AS RESISTOR FOR RC TANK
508
END

FIG. 5

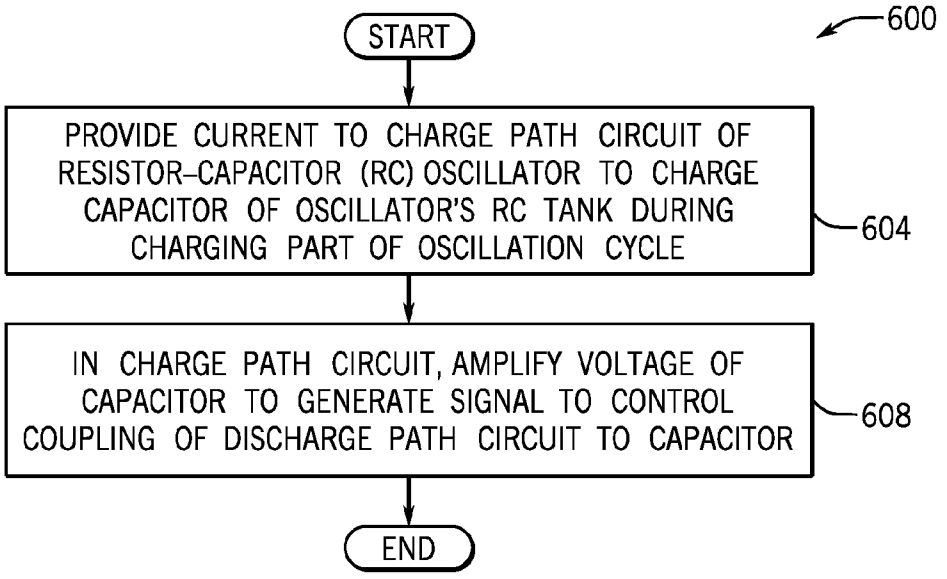

600
START
PROVIDE CURRENT TO CHARGE PATH CIRCUIT OF RESISTOR–CAPACITOR (RC) OSCILLATOR TO CHARGE CAPACITOR OF OSCILLATOR'S RC TANK DURING CHARGING PART OF OSCILLATION CYCLE
604
IN CHARGE PATH CIRCUIT, AMPLIFY VOLTAGE OF CAPACITOR TO GENERATE SIGNAL TO CONTROL COUPLING OF DISCHARGE PATH CIRCUIT TO CAPACITOR
608
END

FIG. 6

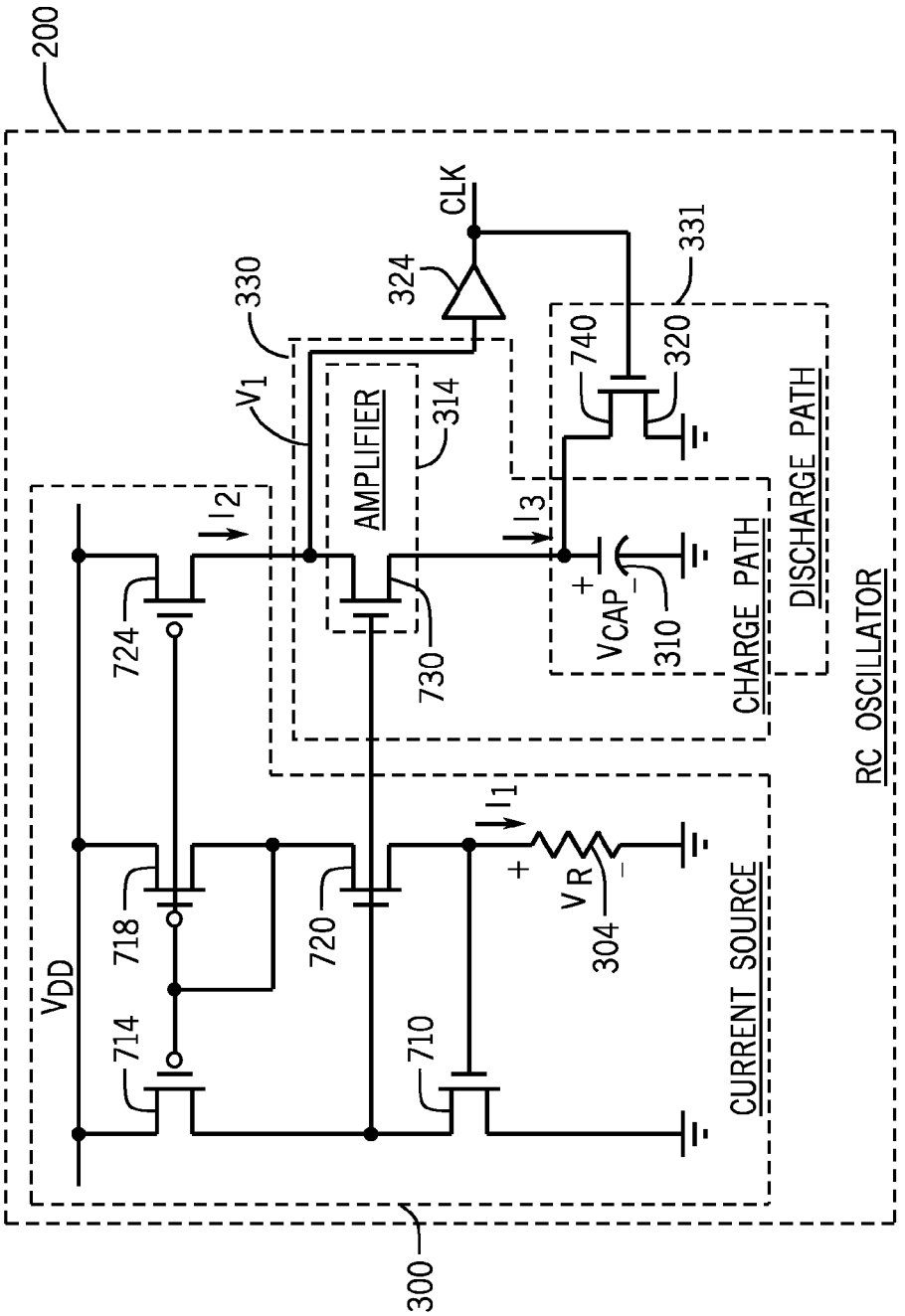

200
CLK
330
324
331
740
320
V1
AMPLIFIER
314
I2
I3
724
730
VCAP
310
CHARGE PATH
DISCHARGE PATH
RC OSCILLATOR
I1
VDD
718
720
VR
304
714
710
CURRENT SOURCE
300

FIG. 7

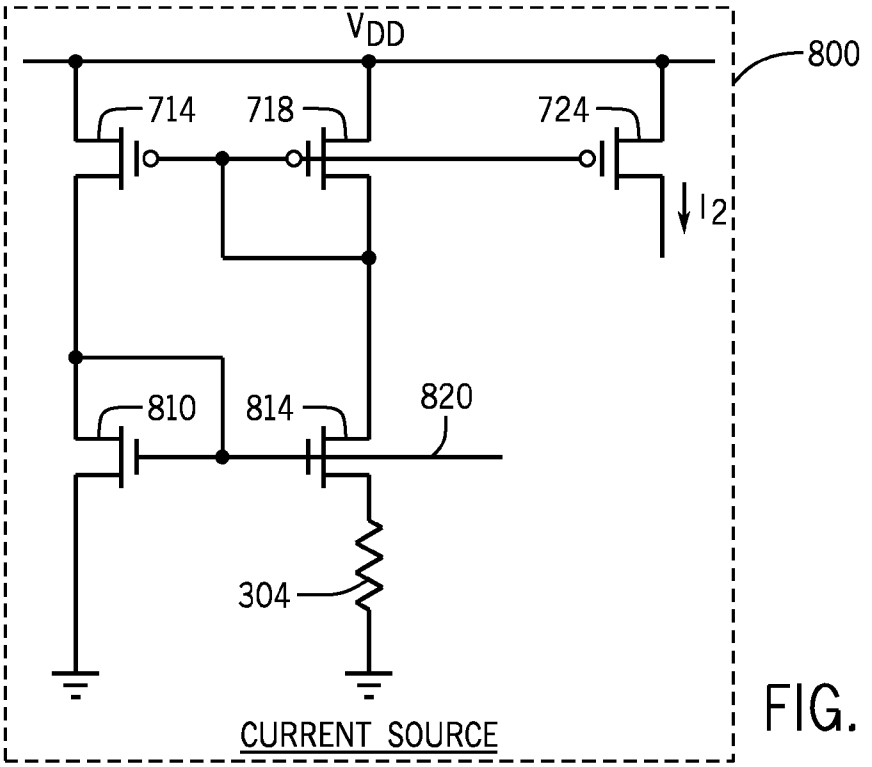

VDD
800
714
718
724
I2
810
814
820
304
CURRENT SOURCE

FIG. 8

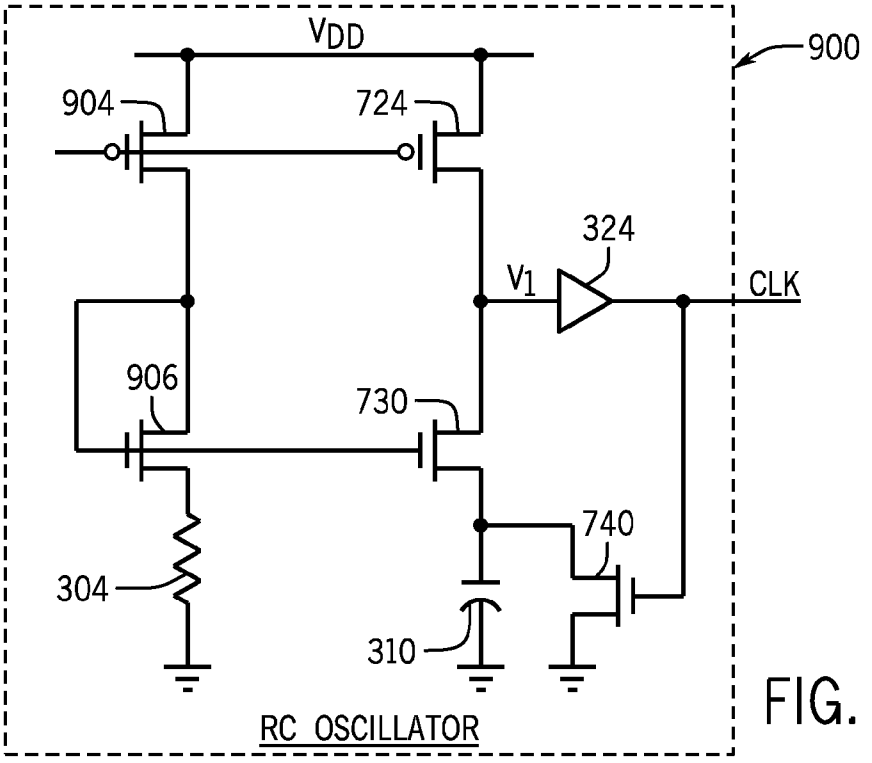

VDD
900
904
724
324
V1
CLK
906
730
740
304
310
RC OSCILLATOR

FIG. 9

RC OSCILLATOR

BACKGROUND

Clock signals may be used in an electronic system for such purposes as synchronizing operations of a processor, keeping track of time and initiating periodic activity. The clock signal is generated by an oscillator, and the frequency of the clock signal typically is regulated by controlling the frequency of the oscillator. One way to control the oscillator's frequency is through the use of a resistor-capacitor (RC) tank, or resonant circuit, which may be part of the same integrated circuit as the oscillator.

SUMMARY

In an example embodiment, a method includes using a current source to provide a charging current to a capacitor of a resistor-capacitor (RC) tank of an RC oscillator. The method includes using a resistor of the current source as a resistor for the RC tank.

In another example embodiment, an apparatus includes a resistor-capacitor (RC) tank circuit, a discharge path and a charge path. The RC tank is formed from a resistor and a capacitor and has an oscillation cycle. In a first part of the cycle, the capacitor is charged, and during a second part of the cycle the capacitor, the discharge path circuit discharges the capacitor. The charge path circuit communicates a charging current to the capacitor. The charge path circuit includes an amplifier to amplify a voltage of the capacitor to generate a signal to control coupling of the discharge path circuit to the capacitor.

In yet another example embodiment, an apparatus includes an integrated circuit, which includes a processor core and a clock system. The clock system includes clock sources, and the clock system is adapted to select a clock signal provided by a given clock source and provide the selected clock signal to at least one component of the integrated circuit. The given clock source includes a resistor-capacitor (RC) oscillator, which includes a current source and an RC tank circuit. The current source provides a regulated current and includes a resistor. The RC tank circuit includes a capacitor and also includes the resistor of the current source to establish a period of the clock signal.

Advantages and other desired features will become apparent from the following drawings, description and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of an electronic system according to an example embodiment.

FIG. **2** is a schematic diagram of a microcontroller unit (MCU) of the electronic system of FIG. **1** according to an example embodiment.

FIG. **3** is a schematic diagram of a resistor-capacitor (RC) oscillator according to an example embodiment.

FIG. **4** is a waveform of a voltage generated by a capacitor charge path circuit of the oscillator of FIG. **3** according to an example embodiment.

FIG. **5** is a flow diagram depicting a technique to use a resistor of a current source as the resistor for an RC tank of an RC oscillator according to an example embodiment.

FIG. **6** is a flow diagram depicting a technique to generate a signal to control coupling of a discharge path circuit to a capacitor of an RC tank of an RC oscillator according to an example embodiment.

FIG. **7** is a more detailed schematic diagram of the RC oscillator of FIG. **3** according to an example embodiment.

FIG. **8** is a schematic diagram of a current source according to a further example embodiment.

FIG. **9** is a schematic diagram of an RC oscillator according to a further example embodiment.

DETAILED DESCRIPTION

An electronic system, such as a microcontroller unit (MCU)-based platform, may be constructed to perform activities using a relatively high frequency clock signal (a clock signal having a frequency in the MegaHertz (MHz) range, for example) and a relatively low frequency clock signal (a clock signal having a frequency in the kiloHertz (kHz) range, for example). For an MCU-based electronic system, the low frequency clock signal may be used for such purposes as supporting generation of a real time clock (RTC), providing a periodic wake up for the MCU to perform calibrations, allowing components of the system to check sensor inputs, or allowing other periodic activities.

Because the low frequency clock signal may be provided during a time of low power consumption for the electronic system, an oscillator providing the clock signal may also be constrained to have a relatively small power demand and thus, operate while consuming a relatively small overall current (a current of a few nanoamperes (nA), for example) while maintaining a reasonable accuracy (an accuracy around five percent, for example).

In accordance with example embodiments, the electronic system uses a resistor-capacitor (RC) oscillator, a relatively low power and accurate oscillator, to provide a low frequency clock signal. The RC oscillator has an RC tank (which may also be referred to as a "resonant circuit," "tank circuit," and so forth) that establishes the resonance frequency for the oscillator. The RC tank includes a resistor and a capacitor; and the oscillation frequency of the oscillator is proportional to the product of the resistor's resistance and the capacitor's capacitance.

For each cycle of oscillation, the RC oscillator charges and then discharges the capacitor of the RC tank. In this manner, the RC oscillator has a charge path circuit to provide a charging current to the capacitor to store energy in the capacitor during a charging part of the cycle, and the RC oscillator has a discharge path circuit to remove the stored energy from the capacitor during a discharging part of the cycle. The voltage of the capacitor rises during charging, and the capacitor is discharged in response to the voltage of the capacitor reaching a voltage that is related to (equal to, for example) the voltage that is generated by a current in a resistor of the RC oscillator.

In accordance with example embodiments, a current source of the RC oscillator provides the charging current that charges the capacitor of the RC tank, and a resistor of the current source serves dual functions: establishing the current that is provided by the current source; and functioning as the resistor of the RC tank. Moreover, in accordance with example embodiments disclosed herein, the charging path circuit of the RC oscillator contains a single-ended amplifier that is constructed to provide a first stage of amplification for a signal that controls coupling of the discharge path circuit to the capacitor at the end of the charging part of the oscillation cycle. In accordance with some embodiments, the amplifier of the charging path circuit may provide most of the amplification for the signal that controls the coupling/decoupling of the discharge path circuit.

Referring to FIG. **1**, as a more specific example embodiment, an electronic system **100** includes a clock system **98** that contains multiple clock sources, including an RC oscillator **200**. In particular, the clock system **98** selects and provides clock signals that may be used for a number of purposes, as further described herein.

The electronic system **100**, in accordance with example embodiments, includes a microcontroller unit (MCU) **24**, which controls various aspects of one or more components **70** of the electronic system **100**. In general, the MCU **24** communicates with the components **70** via communication input/output (I/O) signals **74**, which may be wireless signals; hardwired cables-based signals; and so forth, depending on the particular embodiment. As examples, the components **70** may include such components as a lighting element; an electrical motor; a household appliance; an inventory control terminal; a computer; a tablet; a smart power meter; a wireless interface; a cellular interface; an interactive touch screen user interface; and so forth.

As depicted in FIG. **1**, in accordance with example embodiments, all or part of the components of the MCU **24** may be part of a semiconductor package **110**. In this manner, all or part of the components of the MCU **24** may be fabricated on a single die or on multiple dies, depending on the particular embodiment, and encapsulated to form the semiconductor package **110**.

Referring to FIG. **2** in conjunction with FIG. **1**, in accordance with example embodiments, the MCU **24** contains a processor core **150**, digital components **90** and an analog system **96**. As an example, the processor core **150** may be a 32-bit core, such as an Advanced RISC Machine (ARM) processor core, which executes a Reduced Instruction Set Computer (RISC) instruction set. In further example embodiments, the processor core **150** may be a less powerful core, such as an 8-bit core (an 8051 core, for example). The digital components **90** may be, as examples, a Universal Serial Bus (USB) interface; a universal asynchronous receiver/transmitter (UART) interface; a system management bus interface (SMB) interface; a serial peripheral interface (SPI) interface; timers; and so forth. In general, the digital components **90** may communicate with devices that are external to the MCU **24** via associated I/O signals **74-1**.

The analog system **96** may include various analog components and systems that receive analog signals, such as analog-to-digital converters (ADCs) and comparators; as well as analog components that provide analog signals, such as current drivers. In general, the analog system **96** communicates with devices that are external to the MCU **24** via associated I/O signals **74-2**.

Among its other components, the MCU **24** includes a system bus **130** that is coupled to the digital components **90**, analog system **96** and processor core **150**. A memory system **158** is also coupled to the system bus **130**. The memory system includes a memory controller, or manager **160**, which controls access to various memory components of the MCU **24**, such as a cache **172**, a non-volatile memory **168** (a Flash memory, for example) and a volatile memory **164** (a static random access memory (SRAM), for example). In accordance with example embodiments, the volatile memory **164** and the non-volatile memory **168** may form the system memory of the MCU **24**. In other words, the volatile memory **164** and the non-volatile memory **168** have memory locations that are part of the system memory address space for the MCU **24**.

It is noted that FIG. **2** depicts a general simplified representation of an example MCU architecture, as the MCU **24** have many other components, bridges, buses, and so forth, in accordance with further embodiments, which are not depicted in FIG. **2**. For example, in accordance with further example embodiments, the MCU **24** may have a bus matrix module that responds to slave side arbitration to regulate access to the memory devices of the MCU **24**. Thus, many other embodiments are contemplated, which are within the scope of the appended claims.

The clock system **98** provides one or multiple clock signals at its output(s) **221**, which may be used in the MCU **24** for any of a number of purposes, depending on the particular embodiment. As depicted in FIG. **2**, in some embodiments, the clock system **98** may provide a clock signal to a real time clock (RTC) module **225** of the MCU **24**. The RTC module **225**, in accordance with example embodiments, is essentially a counter that stores data in a way that allows components of the MCU **24** to request a time or a date. The RTC module **225** may include a scheduler to start a given activity or send an interrupt to the processor core **150** when a particular time is reached.

In further embodiments, a clock signal that is provided by the clock system **98** may be used to run a dedicated digital engine, such that a short cycle of activity (**10** to twenty clock cycles, for example) by the digital engine begins in response to the rising edges of the clock signal. In accordance with example embodiments, the clock system **98** may alternate the frequency of a clock signal between relatively high (MHz frequencies, for example) and low (kHz frequencies, for example) frequencies to initiate analog and digital cycles of activity. In this manner, the clock system **98** may regulate provide a relatively low frequency clock signal for several cycles to change analog states, subsequently provide a relatively high frequency clock signal for several cycles initiate digital activity and then the circuitry enters a waiting state for the next low frequency rising clock edge.

In further embodiments, a the clock system **98** may provide a relatively low frequency clock signal that is used to clock a digital watchdog timer of the MCU **24** such that if no activity occurs for a certain number of low frequency clock cycles, the MCU **24** takes a predetermined action due to the inactivity. For example, after a certain number of low frequency cycles of inactivity, the MCU **24** may power down components for purposing of reducing power consumption. As another example, the MCU **24** may reset one or more components after a certain number of low frequency cycles of inactivity, as the inactivity may indicate a hung state.

For a relatively low frequency clock signal, the clock system **98** may select a clock signal (called "CLK" in FIG. **2**), which is provided by the RC oscillator **200**. The clock system **98** may have one or multiple other clock sources **210**, which generally provide different frequency clock signals for the MCU **24** and which may be selected by the clock system **98** for purposes of providing the system's clock signal(s). FIG. **2** schematically depicts selection of the clock sources via a multiplexer **220** that may be controlled (via selection signals **224** provided the processor core **150**, for example) for purposes of selecting the appropriate frequency clock signal(s) that are provided at the output(s) **221** of the clock system **98**. Referring to FIG. **3**, in accordance with example embodiments, the RC oscillator **200** includes a current source **300**; and an RC tank, which is formed from a capacitor **310** and a resistor **304**. As depicted in FIG. **3**, in accordance with example embodiments, the resistor **304** of the RC tank is part of the current source **300**.

The RC oscillator **200** charges and discharges the capacitor **310** in each oscillation cycle of the oscillator **200** to correspondingly form one cycle of the CLK clock signal.

The charging of the capacitor **310** occurs in a charging part of the oscillation cycle. In this part of the cycle, the current source **300** provides a relatively fixed, or constant, current (called "I_2" in FIG. **3**), which produces a charging current (called "I_3") in a charge path circuit (called a "charge path **330**" herein) for the capacitor **310**. In accordance with some embodiments, the magnitude of the I_3 charging current is generally proportional to (equal to, for example) the magnitude of the I_2 current. In the charging part of the cycle, the capacitor **310** charges in response to the I_3 charging current, and a voltage of the capacitor **310** (called "V_{CAP}" in FIG. **3**) corresponding ramps upwardly.

In accordance with example embodiments, the charge path **330** contains a single-ended amplifier **314** that amplifies the V_{CAP} capacitor voltage (as described further herein) to provide a voltage (called "V_1" in FIG. **3**) that is used to control the coupling and decoupling of a discharge path circuit (called a "discharge path **331** in FIG. **3**) to/from the capacitor **310**; and as such, V_1 voltage serves as a signal to control when the charging and discharging parts of the oscillation cycle begin and end.

For the example embodiment that is depicted in FIG. **3**, the discharge path **331** is form by a controlled current path, or switch **320**. In this manner, for the charging part of the cycle, the switch **320** does not conduct, or is turned off; and during the charging cycle, the V_1 voltage generally increases in magnitude over time as the capacitor **310** is being charged and the V_{CAP} capacitor voltage rises. As described further below, due to the charging of the capacitor **310**, the V_1 voltage eventually reaches a voltage, which causes the switch **320** to conduct, or turn on, and consequently begin the discharging part of the cycle in which the capacitor **310** is discharged through the switch to ground. The discharging of the capacitor **310**, in turn, causes the V_1 and V_{CAP} voltages to decrease; and the lowered V_1 voltage causes the switch **320** to turn off, thereby ending the charging part of the current cycle and beginning the charging part of the next cycle.

The magnitude of the I_2 current is generally inversely proportional to the resistance of the current source's resistor **304**, in accordance with example embodiments. In this manner, as depicted in FIG. **3**, the current source **300** produces a current (called "I_1" in FIG. **3**) in the resistor **304**, which is proportional in magnitude to the magnitudes of the I_2 and I_3 currents. The I_1 current produces a voltage (called "V_R" in FIG. **3**) across the resistor **304**. The V_{CAP} capacitor voltage charges at a time rate that is proportional to the I_2 current divided by the capacitance of the capacitor **310**. Because the I_3 and I_1 currents are proportional, the cycle time, in accordance with example embodiments, is proportional to the product of the resistance of the resistor **304** and the capacitance of the capacitor **310** and is independent of the I_1, I_2 and I_3 currents, and when the V_{CAP} capacitor voltage reaches a threshold voltage that is proportional to the resistance of the resistor **304** and the I_1 current, the charging of the capacitor **310** ends and the discharging of the capacitor **310** begins. The cycle time is the threshold voltage divided by the time rate, in accordance with example embodiments. The charging part of the oscillation cycle is proportional to the product of the resistance of the resistor **304** and the capacitance of the capacitor **310**. In accordance with example embodiments, the discharging part of the cycle is a set by a propagation delay time (described below); and the product of the resistance of the resistor **304** and the capacitance of the capacitor **310** establishes the periodic frequency of the oscillation cycle.

In accordance with example embodiments, the RC oscillator **200** includes a digital buffer **324** that pulse shapes the V_1 voltage (i.e., sharpens the rising and falling edges of the V_1 voltage) to provide the CLK signal at the output of the buffer **324**. It is noted that depending on the particular embodiment, the oscillator **200** may contain frequency dividers and other circuitry to change the frequency of the CLK signal, change the duty cycle of the CLK signal, and so forth. As described further herein, in accordance with example embodiments, the propagation delay of the digital buffer **324** sets the duration of the discharge part of the oscillation cycle.

Thus, referring to FIG. **5**, in accordance with example embodiments, a technique **500** includes using (block **504**) a current source to provide a charging current to a capacitor of a resistor-capacitor (RC) tank of an RC oscillator. Pursuant to the technique **500**, a resistor of the current source is used (block **508**) as a resistor for the RC tank.

A potential advantage of using a resistor of a current source as part of the RC tank is that die area is conserved (i.e., one less resistor is used). Another potential advantage is that current (and therefore power consumption) may be reduced due to the use of part of the current source for dual functions.

Referring back to FIG. **3**, in accordance with some embodiments, a particular advantage of having the single-ended amplifier **314** disposed in the charge path **330** is that the amplifier **314** may be used in place of an input stage of a comparator that may otherwise be used to amplify the V_{CAP} capacitor voltage. In this manner, the amplifier **314**, in accordance with example embodiments, provides most of the amplification for the CLK signal that controls the coupling of the discharge path circuit **331** to the capacitor **310**. FIG. **4** depicts an example magnitude versus time waveform of the V_1 voltage for an example oscillation cycle from time T_0 to time T_3. Charging of the capacitor **310** occurs from time T_0 to time T_2; and discharging of the capacitor **310** occurs from time T_2 to time T_2.

From time T_0 (when the capacitor **310** discharged) to time T_1, the magnitude of the V_1 voltage generally linearly ramps upwardly and generally follows the corresponding ramping of the V_{CAP} capacitor voltage. Near or at time T_1, the magnitude of the V_1 voltage reaches a threshold voltage magnitude (called "V_2" in FIG. **4**), which is set by the resistance of the resistor **304**.

As further described herein, when the magnitude of the V_1 voltage reaches the V_2 threshold at time T_1 the amplification that is applied by amplifier **314** of the charge path **330** increases. While the V_{CAP} capacitor voltage is lower than the V_2 voltage, the V_1 voltage is slightly higher than the V_{CAP} capacitor voltage. As the V_{CAP} capacitor voltage approaches and exceeds the V_2 voltage, the V_1 voltage increases rapidly from time T_1 to time T_2, as depicted in FIG. **4**, which causes the voltage at the control terminal of switch **320** to a larger magnitude (called "V_3" in FIG. **4**) turn on the switch **320** and trigger discharging of the capacitor **310**. The discharging the capacitor **310** occurs from time T_2 to time T_3. At time T_3, the capacitor **3120** is discharged and the switch **320** opens to begin another oscillation cycle.

Thus, referring to FIG. **6**, in accordance with example embodiments, a technique **600** includes providing (block **604**) a current to a charge path circuit of an RC oscillator to charge a capacitor of the oscillator's RC tank during the charging part of the oscillator's cycle. The technique **600** further includes amplifying a voltage of the capacitor to generate a signal to control coupling of a discharge path circuit of the RC oscillator to the capacitor.

A potential advantage in using an amplifier in the charge path is that die area, otherwise consumed by a comparator, for example, may be conserved; and another potential advantage is that power may be conserved due to reduction in circuitry.

Referring to FIG. **7**, in accordance with example embodiments, the current source **300** is a V_{GS}/R current source circuit, which is a self-biased current source. The current source **300** includes an N-channel metal-oxide-semiconductor field-effect-transistor (NMOSFET) **710**, which has its gate and source coupled across the resistor **304**. Thus, the voltage across the resistor **304** is equal to the gate-to-source (V_{GS}) of the NMOSFET **710**; and the magnitude of the I_1 current is equal to the quotient of the V_{GS} voltage of the NMOSFET **710** divided by the resistance of the resistance **204**. For this example embodiment, the source of the NMOSFET **710** is coupled to ground; one terminal of the resistor **304** is coupled to ground; and the other terminal of the resistor **304** is coupled to the gate of the NMOSFET **710**. An NMOSFET **720** of the current source **300** has its source coupled to the gate of the NMOSFET **710**, and a gate of the NMOSFET **720** is coupled the drain of the NMOSFET **710**.

A current mirror of the current source **300**, which is formed from P-channel MOSFETs (PMOSFETs) **714** and **718**, mirrors the I_1 current into the drain-to-source path of the NMOSFET **710** (i.e., into the current-controlled path of the NMOSFET **710**). In this regard, the source of the PMOSFET **718** is coupled to the V_{DD} supply voltage, and the drain of the PMOSFET **718** is coupled to the drain of the NMOSFET **720**. Moreover, the gate and drain of the PMOSFET **718** are coupled together. The source of the PMOSFET **714** is coupled to the V_{DD} supply voltage, a gate of the PSMOFET **714** is coupled to the gate and drain of the PMOSFET **718**; and the drain of the PMOSFET **714** is coupled to the drain of the NMOSFET **710**.

In accordance with example embodiments, the I_1 current has a magnitude equal to the gate-to-source voltage (V_{GS}) of the NMOSFET **710** divided by the resistance (R) of the resistor **304**, or V_{GS}/R, which may be approximated as "V_t/R" (where "V_t" represents the MOSFET threshold voltage of the NMOSFET **710**).

As depicted in FIG. **7**, the current source **300** further includes a PMOSFET **724** that additionally mirrors the I_1 current to produce the I_2 current in the charge path **330**. The I_2 current is proportional to the I_1 and may be equal to, a multiple of, or a fraction of the I_1 current, depending on the relative aspect ratios of the PMOSFETs **718** and **724**. The source of the PMOSFET **724** is coupled to the V_{DD} supply voltage; the gate of the PMOSFET **724** is coupled to the gates of the PMOSFETs **714** and **718**; and the drain of the PMOSFET **724** provides the I_2 current.

The amplifier **314** of the charge path **330** includes an NMOSFET **730**, in accordance with example embodiments. In this regard, the I_2 current passes through the drain-to-source path of the NMOSFET **730** and, for this example, is near or equal to the I_3 current, as negligible current is assumed to be communicated to the digital buffer **324**. The drain of the NMOSFET **730** is coupled to the drain of the PMOSFET **724**; the gate of the NMOSFET **730** is coupled to the gate of the NMOSFET **720**; and the source of the NMOSFET **730** is coupled to the input of the current buffer **324** and the non-ground terminal of the capacitor **310**.

Also for the example embodiment depicted in FIG. **7**, the switch **320** includes an NMOSFET **740**, whose drain-to-source path is coupled across the capacitor **310**. The gate of the NMOSFET **740** is coupled to the CLK clock signal, i.e., coupled to the output of the digital buffer **324**.

The digital buffer **324** may take on numerous forms, depending on the particular embodiment. In an example embodiment, the digital buffer **324** is formed from an even number of serially-coupled complementary metal-oxide-semiconductor (CMOS) inverters (i.e., a CMOS inverter chain).

The RC oscillator **200** operates as follows. In general, the NMOSFETs **720** and **730** are considered to be matching transistors for this example embodiment. The effective charging reference voltage is determined by the V_R resistor voltage. As long as the V_{CAP} capacitor voltage is less than the V_R resistor voltage, the currents through the drain-to-source paths of the NMOSFETs **720** and **730** are equal or fixed ratios of each other, depending on the aspect ratios of the PMOSFETs **718** and **724**.

When the capacitor **310** is being charged, the NMOSFET **740** does not conduct, or is "turned off," and the V_{CAP} capacitor voltage has a relatively low magnitude. Due to the charging of the capacitor **310**, the V_{CAP} capacitor voltage ramps upwardly. The NMOSFET **730** is operating in a linear mode of operation during the initial charging of the capacitor **310**, which causes the magnitude of the V_1 voltage to generally follow the magnitude of the V_{CAP} voltage. When the V_{CAP} capacitor voltage reaches the V_R resistor voltage, the magnitude of the I_3 current decreases abruptly, due to the gates of the NMOSFETs **720** and **730** being coupled together and the NMOSFET **730** turning off. The PMOSFET **724** pulls the V_1 voltage to or near the V_{DD} supply voltage, the I_2 current decreases and the NMOSFET **740** turns on. Thus, at this point, the charge path **330** is decoupled from the capacitor **310**, and the discharge path **331** is coupled to the capacitor **310**.

In accordance with example embodiments, the digital buffer **324** introduces a propagation delay that sets the duration of the discharging part of the oscillation cycle. In this manner, the turning on of the PMOSFET **724** causes the V_1 voltage to be pulled toward ground. However, the appearance of the lower V_1 magnitude at the gate of the NMOSFET **740** is delayed by the propagation delay of the digital buffer **324**. The propagation delay of the digital buffer **324** (or other introduced delay, depending on the particular embodiment) is selected to ensure that the capacitor **310** is fully discharged before the charging part of the cycle begins. As an example, in accordance with some embodiments, the propagation delay is a function of the number of CMOS inverters that are used to form the digital buffer **324**.

Other embodiments are contemplated, which are within the scope of the appended claims. In this manner, FIG. **8** depicts a current source **800** in accordance with a further example embodiment. The current source **800** is a delta V_{GS}/R current source circuit. Elements of the current source **800** shared in common with the current source **300** are denoted using similar reference numerals. The current source **800** has NMOSFETs **810** and **814** that replace the NMOSFET **710** of the current source **300**. In this regard, the NMOSFET **810** has its source coupled to ground and its drain and gate coupled together. Moreover, the drain of the NMOSFET **810** is coupled to the drain of the PMOSFET **714**. The gate of the NMOSFET **814** is coupled to the gate of the NMOSFET **810**, the source of the NMOSFET **814** is coupled to node **305**, and the drain of the NMOSFET **814** is coupled to the gate and drain of the PMOSFET **718**. Moreover, the gates of the NMOSFETs **810** and **814** are coupled (as indicated by terminal **820**) to the NMOSFET **730** (see FIG. **7**).

In accordance with example embodiments, the I_2 current has a magnitude that generally proportional to "(V_{GS1}–

V_{GS2})/R," where "V_{GS1}" and "V_{GS2}" represent the gate-to-source voltages of the NMOSFETs **810** and **814**, respectively; and "R" represents the resistance of the resistor **304**. The V_{GS1}–V_{GS2} voltage is largely determined by the relative aspect ratios of the PMOSFETs **718** and **714** and the relative aspect ratios of NMOSFETs **814** and **810**, which also set the relative current densities in the NMOSFETs **810** and **814**. In some embodiments **810** and **814** could be chosen have different threshold voltages, and the I_2 current may be approximated as "(V_{t1}–V_{t2})/R," where "V_{t1}" and "V_{t2}" represent the MOSFET threshold voltages of the NMOSFETs **810** and **814**, respectively.

The RC oscillator may use other current sources, in accordance with further embodiments.

As another example of a further embodiment, FIG. **9** depicts an RC oscillator **900** that does not include a current source, but rather, the resistor **304** of the RC tank receives a reference current. In general, the RC oscillator **900** has features similar to other RC oscillators discussed herein, with the same reference numerals being used to denote similar components and different reference numerals being used to denote the new features. Unlike the oscillator **200**, for the oscillator **900**, a PMOSFET **904** mirrors a current from a current source (not depicted in FIG. **9**), and this mirrored current is routed through the resistor **304**, which is coupled in series with the source-to-drain path of the PMOSFET **904**. Moreover, an NMOSFET **906** has its drain-to-source path coupled in series with the source-to-drain path of the PMOSFET **904** and the resistor **304**. As shown in FIG. **9**, the drain and gate of the NMOSFET **906** are coupled together; and the gate of the NMOSFET **906** is coupled to the gate of the NMOSFET **730**. The resistor **304** is coupled between the source of the NMOSFET **906** and ground.

As yet another example of a further example embodiment, the circuitry that is described herein may be replaced by equivalent CMOS circuitry in which the PMOSFETs and NMOSFETS are interchanged, as can be appreciated by one of ordinary skill in the art.

While a limited number of embodiments have been disclosed herein, those skilled in the art, having the benefit of this disclosure, will appreciate numerous modifications and variations therefrom. It is intended that the appended claims cover all such modifications and variations.

What is claimed is:

1. A method comprising:

using a current source to provide a charging current to a capacitor of a resistor-capacitor (RC) tank of an RC oscillator;

using a resistor of the current source as a resistor for the RC tank; and

communicating the charging current to the capacitor using a charging path, wherein using the charging path comprises communicating the charging current to the capacitor using an amplifier and using the amplifier to amplify the voltage to generate a signal to turn on a discharge path to discharge the capacitor, wherein using the amplifier to amplify the voltage comprises operating a first transistor in a linear mode of operation to communicate the charging current to the capacitor and transitioning the first transistor to an off state near or at the end of a first part of an oscillation cycle for the RC oscillator to increase the amplification of the signal.

2. The method of claim **1**, further comprising using a resistance of the resistor to regulate the charging current.

3. The method of claim **1**, wherein:

the first transistor has a controlled current path in series with the capacitor; and

using the resistor comprises providing a second transistor having a controlled current path in series with the resistor and coupling control terminals of the first and second transistors together.

4. The method of claim **1**, further comprising:

using the RC oscillator in a clock system for an electronic device to provide a relatively low frequency clock signal to change a state of an analog component of the electronic device and using a clock source of the clock system other than the RC oscillator to provide a relatively high frequency clock signal to change a state of a digital component of the electronic device.

5. The method of claim **1**, further comprising activating a transistor to discharge the capacitor.

6. The method of claim **1**, wherein using the current source comprises using a V_{GS}/R current source or a delta V_{GS}/R current source to provide the charging current.

7. An apparatus comprising:

a resistor-capacitor (RC) tank circuit formed from a resistor and a capacitor and having an oscillation cycle comprising a first part of the cycle in which the capacitor is charged and a second part of the cycle in which the capacitor is discharged;

a discharge path circuit to discharge the capacitor during the second part of the cycle; and

a charge path circuit to communicate a charging current to the capacitor, wherein the charge path circuit comprises an amplifier to communicate the charging current and to amplify a voltage of the capacitor to generate a signal to control coupling of the discharge path circuit to the capacitor, wherein the amplifier comprises a transistor to operate in a linear mode of operation to communicate the charging current to the capacitor and transition to an off state near or at the end of the first part of the cycle to increase the amplification of the signal.

8. The apparatus of claim **7**, wherein the amplifier comprises a single-ended amplifier to amplify the voltage.

9. The apparatus of claim **7**, wherein the discharge path circuit comprises a switch to be selectively turned on by the signal to discharge the capacitor.

10. The apparatus of claim **7**, further comprising a digital buffer to reshape the voltage of the capacitor to generate a clock signal.

11. An apparatus comprising:

an integrated circuit comprising a processor core and a clock system comprising a plurality of clock sources and being adapted to select a clock signal provided by a given clock source of the plurality of clock sources and to provide the selected clock signal to at least one component of the integrated circuit, wherein the given clock source comprises a resistor-capacitor (RC) oscillator comprising:

a current source to provide a regulated current and comprising a resistor;

an RC tank circuit comprising the resistor and a capacitor to establish a period of the clock signal; and

a charge path circuit to charge the capacitor using a charging current, wherein the charge path circuit comprises an amplifier to communicate the charging current to the capacitor and amplify a voltage of the capacitor to generate a signal to control operation of a discharge circuit to discharge the capacitor,

wherein the RC oscillator is associated with an oscillation cycle, and the amplifier comprises a first transistor to operate in a linear mode of operation to communicate the charging current to the capacitor and transition to an

off state near or at the end of a first part of the oscillation cycle to increase the amplification of the signal.

12. The apparatus of claim **11**, wherein a resistance of the resistor controls a magnitude of the charging current.

13. The apparatus of claim **11**, wherein the current source comprises:

a second transistor having a first controlled current path in series with the resistor;

a third transistor having a second controlled current path in series with the capacitor; and

a current mirror to couple the first and second controlled current paths together.

14. The apparatus of **11**, wherein the current source comprises a V_{GS}/R current source or a delta V_{GS}/R current source.

* * * * *