Ultra-Low Voltage Nanoelectronics Powered Directly, and Solely, from a Tree

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***Abstract*— Complex patterns of electrical potential differences exist across the structure of a tree. We have characterized these voltages and measured values ranging from a few mV to a few hundred mV for Bigleaf maples. These potential differences provide a unique opportunity to power nanoelectronic circuits directly from a tree. We have designed, constructed, and successfully tested two integrated circuits powered solely through a connection to Bigleaf maple trees. The first circuit, built in a 130 nm technology, creates a stable 1.1 V supply from input voltages as low as 20 mV and can be deployed to generate a usable voltage level for standard circuits. The second circuit fabricated in 90 nm technology is a timer operating at 0.045 Hz and can be used for time keeping in stand-alone sensor network nodes. The boost circuit and timer consume 10 nW and 2.5 nW of power during operation, respectively.**

I. Introduction

It has been demonstrated that measureable, albeit small, electrical potentials exist in various common plants and trees [1][2]. These voltages have recently been attributed to a pH difference between xylem tissue and soil content [3]. In this paper, we tap into this power source by leveraging advances in integrated circuit (IC) design techniques allowing extremely low voltage and low power circuit operation. As nano-scale integrated circuit advances lead to the development of electronics which require diminishing amounts of power for operation, one can re-examine naturally occurring electrical phenomena to find viable power sources for these systems. Environmental sensing networks for climatic and wildlife monitoring in areas of limited accessibility often rely on batteries which must be maintained and replaced. These networks would benefit from self-sustaining power sources.

By using the bioelectric properties of living trees, we have tapped a natural source of energy to power electronic circuits, eliminating the need for conventional chemical batteries. This energy source could foster the development of new applications for electronics and expand the number of locations in which they operate.

We first provide an overview and measured results of the tree-based power source in Section II. In Section III, we introduce two integrated circuits that were designed for ultra-low voltage and low power operation and present results showing successful operation from the tree power source.

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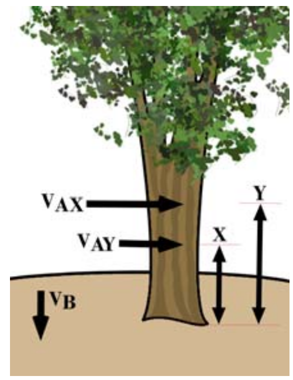

Fig. 1. Measurement points for characterizing the potential difference between the vascular tissue and a ground reference. V_{AX} and V_{AY} are potentials of steel nails inserted in the tree trunk X cm and Y cm above the ground respectively. V_B is the potential of a steel nail inserted in the topsoil 30 cm away from the tree. $V_{AX-AY} = V_{AX} - V_{AY}$ and $V_{AX-B} = V_{AX} - V_B$.

II. Power Source

A. Overview

Both constant voltages and transient pulses have been routinely observed in the tissues of living organisms. Plant cells maintain an inside-negative potential of approximately 60 mV regulated by channels across the cell membrane. Electrical signaling is accomplished through action potentials in the phloem of vascular plants in a manner electrically and chemically similar to those in animal nervous systems [4]. Neither phenomenon has been utilized as a sustainable power source, as traditionally neither has been deemed capable of providing sufficient voltage and power drive capability.

The xylem sap of a vascular plant is at a lower electric potential than the soil near the roots [1]. This trans-root potential (TRP) in the xylem conduit has been observed over long periods of time in plant physiological studies [2][5]. The H+ ion concentration gradients affected by H+-ATPase in the stelar cell membranes contribute to the cells' membrane potentials, resulting in a negative potential in xylem parenchyma relative to the symplast [6]. In higher plants, xylem serves as the primary means of translocation of inorganic ions. Stelar cells facilitate the uptake of K+ ions through outwardly-rectifying channels in the cell membranes. The TRP is correlated with the K+ concentration of xylem sap, increasing by about 50 mV with each 10-fold increase in K+ activity [7]. The magnitude of the TRP measured in previous long-term studies was on the order of hundreds of millivolts, with variations occurring both daily [2] and seasonally [5]. These results suggest that the TRP can serve as a stable power source if the operating voltage and power of the integrated circuits were sufficiently low.

B. Measurements

To determine the sustainability of a tree-based voltage source for low power circuitry, we measured potential differences in Bigleaf maple trees over a period of one week. The potentials of interest were defined at locations in the tree structure as shown in Figure 1. The tree supplied power to a resistive load constantly throughout the test. Representative results are shown in Figures 2 and 3. All measured V_{AX-B} potentials consistently indicated a negative potential with respect to the ground electrode; however, such a trend could not be established for V_{AX-AY} potentials as the polarity of this voltage and its magnitude was not a simple function of X-Y.

As the load impedance decreased a steep decline in output voltage was observed (Fig. 3). The tree power source exhibits low voltages and high impedances, both of which make the direct operation of integrated circuits difficult.

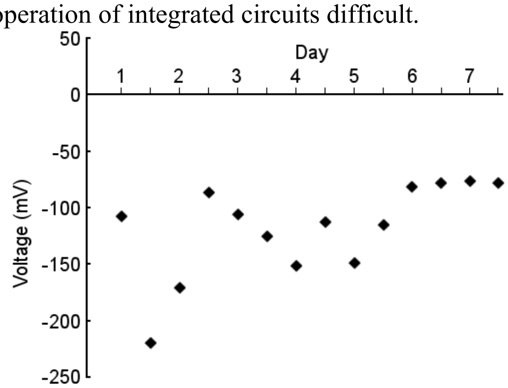

Fig. 2. Measured voltage levels across a 100 kΩ load referenced to soil(V_{AX-B}) with X = 50 cm over a seven day period. Measurement error +/- 10 μV.

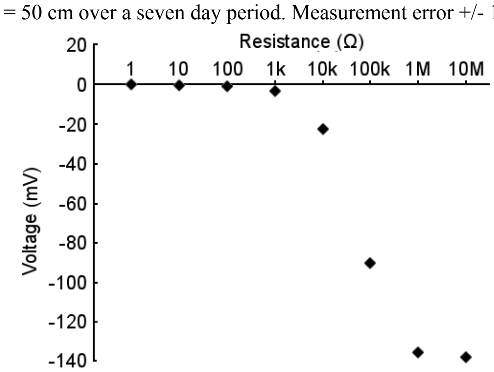

Fig. 3. Measured voltages (V_{AX-B}) across various loads referenced to soil. X = 30cm.

III. Ultra-Low Power, Low Voltage ICs

Commercial ICs require supply voltages greater than 1V, eliminating the possibility of operating from a tree power source. In this section, we introduce two specialized ICs that were successfully operated solely from a connection to a sub-1V, high impedance tree power source.

A. Boost Converter

A switching boost converter generates a DC voltage higher than that of the circuit's power source by shorting an inductor across the source and periodically redirecting the current path to the output. We designed and fabricated a voltage boost converter IC to generate a 1.1 V supply from voltages as low as 20 mV, allowing operation of standard electronics from tree power sources [8]. We operate this boost converter in short bursts with the aid of a low-power voltage supervisor circuit, allowing less than 10 nW of average quiescent power consumption. We fabricated the circuit in a 130 nm CMOS process.

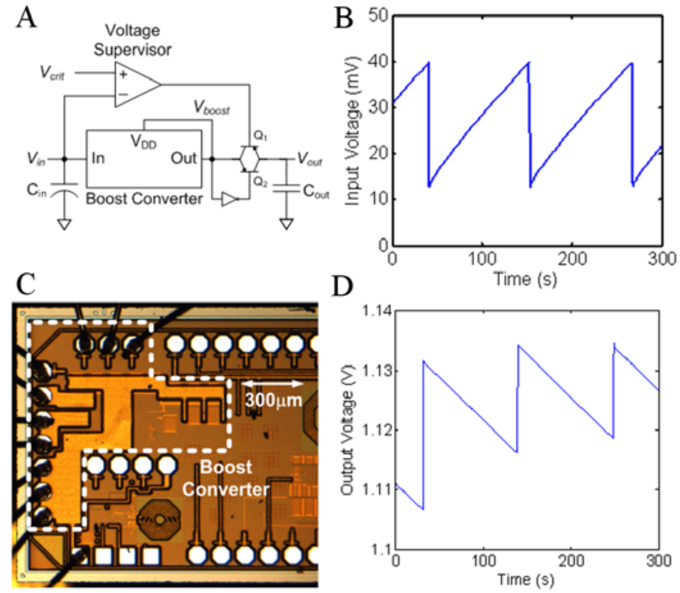

Fig. 4. The boost converter, (A) connection diagram, (B) measured input voltage from a tree connected to the circuit as a functional of time, (C) optical microscope image of a functional chip. The area occupied by the boost convertor is marked with dotted lines. The scale bar is 300 μm, (D) measured output voltage of the circuit verifying that the small input voltage levels have been converted to 1.1 V usable for conventional electronics.

Figure 4A shows the boost converter circuit schematic and Figure 4C shows a microscope image of the chip with the boost circuit outlined. A low leakage storage capacitor C_{out} is used to store charge at 1.1 V. This stored charge is used to power the voltage supervisor and activate the boost converter. C_{out} must be pre-charged during installation but will be re-charged indefinitely by the boost converter. Capacitor C_{in} (4.7 mF) is charged over several seconds through the tree power source. During this charging time, the boost converter is powered down. The converter output V_{boost} is zero and the converter draws no power from capacitor C_{in}. Once the voltage charges above the critical voltage V_{crit}, the supervisor section of the circuit enables the boost converter, and energy from the capacitor C_{in} is pumped into C_{out} at a significantly higher voltage.

While in boost mode, the converter continuously discharges C_{in}. Eventually, C_{in} discharges until there is no longer sufficient voltage to keep the boost converter active. The converter then shuts down and the voltage V_{boost} drops to 0 V. In this phase, the converter consumes no power, the input voltage is allowed to charge up again, and the cycle repeats. Figure 4B shows measured data of the charging waveform of the input voltage and Fig 4D shows the output voltage stored in C_{out} over five minutes. Since the input voltage threshold V_{crit} is set to 40 mV, the input voltage is "clamped" to 40 mV. The average output voltage increases slowly over time and converges at approximately 1.13 V. The duty cycle of the boost converter is a function of the available tree power, the load power, and the boost converter efficiency. For example, for the tree measured in Figure 3, assuming an active load power requirement of 10 μW, the available duty cycle would be roughly 0.4% (0.1 hours active per day).

B. Low Frequency Timer

A timer, or clock, is a critical component of most electronic systems. For wireless environmental monitors, for example, one may want to issue a sensor-read command every second or so. Construction of a very low frequency oscillator that requires large passive components (inductors, resistors, and capacitors) presents a significant challenge due to the limits imposed by CMOS fabrication processes on the size of these components. A creative approach to emulate large resistances has been to take advantage of the extremely small tunneling current flowing onto a floating gate node to create a large Resistive-Capacitive (RC) time constant τ [9]. Taking advantage of this technique, we constructed a nanowatt sub-Hz oscillator in a 90 nm CMOS process using an analog operational transconductance amplifier Schmitt trigger topology. Given the measurements presented in Section II, the clock must operate with a few hundred mV of supply voltage and dissipate less than 1 μA of current to allow continuous operation from a tree power source. Alternately, the low power timer can be operated from the 1.1V output of the boost converter.

A conceptual diagram of the oscillator circuit topology is shown in Figure 5A. The oscillation frequency is determined by charging/discharging an RC network until a high/low internally-generated reference level is exceeded (*VH* and *VL*). To synthesize an extremely large resistor, we utilized the gate leakage through a thin-oxide (16 Å) Metal Oxide Semiconductor Field Effect Transistor (MOSFET) to charge/discharge a thick-oxide (50 Å) Metal Oxide Semiconductor Capacitor (MOSCAP) [10]. Figure 5B shows a microscope image of the fabricated chip with the oscillator circuit area highlighted. The circuit operates over a supply voltage range of 350 mV to 1.2V when powered by a traditional voltage source. The circuit presents a high impedance to the supply, and can be directly interfaced with a tree as a power supply. We powered the oscillator solely by such a connection to a Bigleaf Maple. A typical output voltage measurement is shown in Figure 5C. The measured oscillation frequency of the circuit was 0.045 Hz.

IV. CONCLUSION

The rapid advance of nanoelectronics has enabled the construction of circuits with exceedingly small energy and power requirements. Access to such technology merits a second look at naturally occurring phenomena that have been previously dismissed as either noise-like or too insignificant as a usable energy source. One such phenomenon is electrical potentials observed in trees. We have investigated the potential differences found in Bigleaf maples and have designed, built, and tested two nanoelectronic circuits solely powered by a connection to a tree. Our hope is that the demonstrations here catalyze research in interfacing nano-scale electronics with other natural phenomena and put added emphasis on power as an important and integral part of nanotechnology.

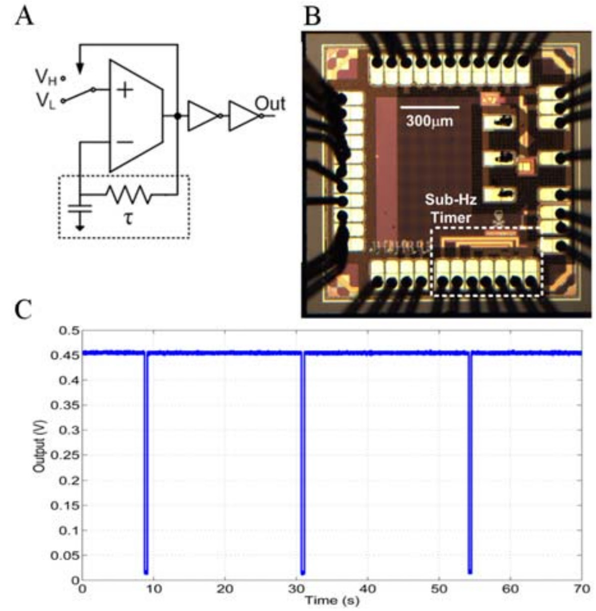

Fig. 5. The architecture of the sub-Hz floating gate oscillator is shown in (A) where a large time constant results from the effective resistance of a transistor gate leakage due to electron tunneling. (B) Shows a microscope image of a chip fabricated in a 90 nm CMOS technology with the oscillator area highlighted. (C) Measured output voltage of the oscillator vs. time verifying proper operation. The circuit was solely powered by a connection to a Bigleaf Maple tree.

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Note Added in Proof: It has come to our attention that the U.S. Patent Office has issued patent No. US 7,466,032B2 to Voltree Power, of Canton, MA, on December 16, 2008. The patent is entitled "Power from a non-animal organism " and broadly covers circuitry fed by a tree-ground potential or other similar non-animal sources.