PRACTICAL ISSUES USING E-POT CIRCUITS

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ABSTRACT

Analog VLSI circuits benefit greatly from tunable, on-chip reference voltages such as the electronic potentiometer (e-pot). This paper examines two vital features of the e-pot: the ability to hold a constant reference voltage and the capability to program it quickly. Empirical data is presented verifying long-term voltage storage, and measurements also show how quickly the e-pot may be programmed as a function of bias voltage.

Dynamically adjustable reference voltages are a fundamental requirement of analog, mixed-signal, and neuromorphic IC's. Because pins are a finite resource, providing all the necessary analog voltages from off-chip is unrealistic for a large system. Yet, a user cannot easily tune a traditional on-chip voltage reference. Furthermore, these references are often inadequate because the output voltage they provide only has a finite number of possibilities (one in the simplest case). The electronic potentiometer, or *e-pot*, has been presented as a practical, user-friendly alternative in the selection of a voltage reference [1]: its design is shown in Fig. 1. An arbitrarily long array of e-pots consumes a small number of pins, permits individual addressing of its e-pot elements, and requires additional power supplies only while the reference voltages (i.e. the e-pots) are being programmed. The e-pot is small, easily adjustable by a user, and can supply a voltage range that is nearly rail-to-rail. Its storage is non-volatile, and its programming is precise and reasonably fast. A few features of the e-pot are addressed in this paper. Since it is worthwhile to know how well an e-pot holds its reference value, the non-volatile nature of the e-pot is studied as a function of time and temperature. Also, the programming speed is examined, so that we may know (a) what supply voltages are necessary to program at certain speeds, and (b) what is the fastest possible speed for programming the device.

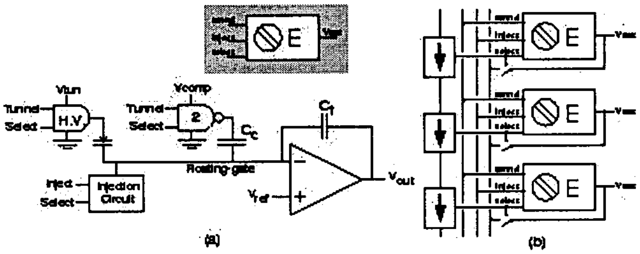

Fig. 1. By storing analog voltages on chip, e-pots allow pins otherwise used for bias voltages to be freed up for I/O. (a) This is the schematic of a single e-pot cell. Charge is removed from the floating gate through tunneling. The tunneling voltage is switched with a high-voltage, differential amplifier, which is built with lightly-doped-drain nFETs. Charge is added to the floating gate through hot-electron injection. The high-voltage amplifier was shown previously [1] (b) This is an array of e-pots: individual cells are addressed with a shift register. The tunnel, inject, and select lines carry digital signals. Currently these elements can be used in standalone operation and are built into our current IC chip padframe for plug-and-play capabilities.

1. LONG-TERM RELIABILITY

A good voltage reference must remain essentially constant, even after a long time has passed. So, it is worth studying how much an e-pot's voltage moves over long periods of time. Figure 2 shows the movement of an e-pot array after a long period of time; for this experiment, the array was programmed to approximately fit a sine function. (The reader may be interested to know that the e-pot can be programmed with much better precision than is shown here: to see a highly accurate fit of a sine function to an e-pot array, see [1].) As shown in Fig. 2, we programmed thirty-nine e-pots to a given value and measured them over a period of fourteen days. Drift of an e-pot's mean output voltage over several days is very slight: both plots show that the e-pots successfully hold their values to within a few millivolts. However, sampling an e-pot's voltage over an integral number of days can be misleading, because it hides cyclical variations of the e-pot voltages around a constant mean value. We have found the frequency of these periodic oscillations

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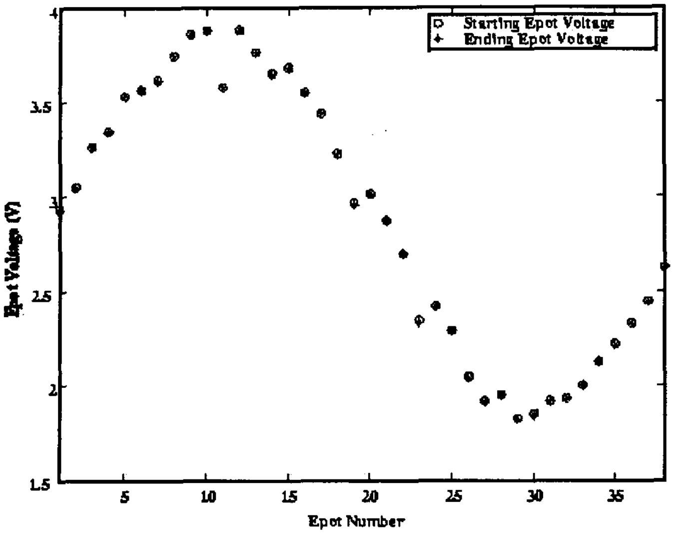


Fig. 2. This figure shows the values of the e-pot array. They were programmed to a rough sine wave to make it obvious that the initial conditions were not random and also to show the e-pot's viability over a range of voltages. The circles represent the starting values. The stars represent the ending values 14 days later. It is clear from this plot that the e-pot voltages do not move very much.

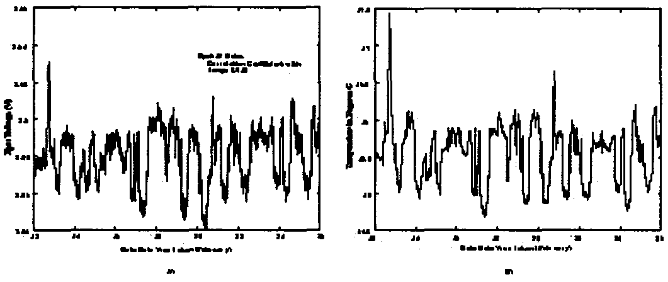


Fig. 3. A)We chose one E-pot to show aclose up view of its voltage. You will notice that it varies considerably, however it is highly correlated to the temperature data shown in **B)**. In fact, the correlation coefficient is 0.915. In both cases, we are plotting data (voltage or temperature) versus day.

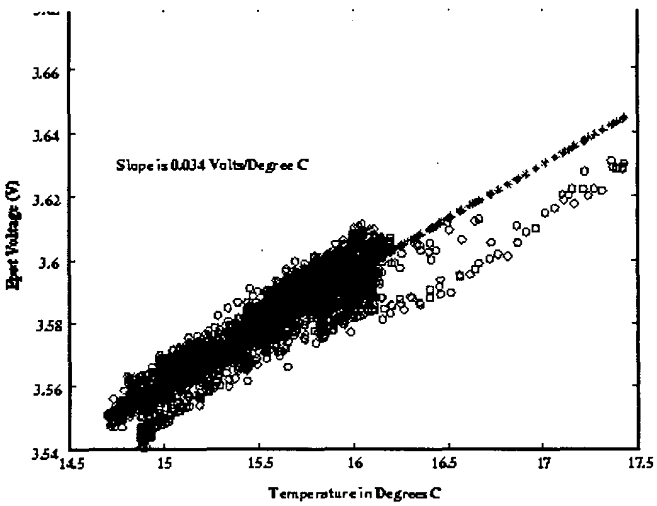


Fig. 4. This figure shows a plot of E-pot output voltage versus temperature. Although there is a voltage variance over a particular temperature, it is easy to see the trend that there is a 0.034V change in output voltage for every degree Celcius change.

to be approximately one cycle per day. Because of this periodicity, we believe that the main cause of the variations is the shift in the laboratory's air temperature throughout the course of a day. For the experiment discussed in Fig. 2, these variations can be seen for the voltage of the array's twelfth element in Fig. 3.

To ensure small variations in an e-pot's voltage as shown above, the tunneling junction's voltage must be handled properly when not being programmed. Figure 5 presents several possible states for the tunneling capacitor. Electrons trapped in the tunneling capacitor's dielectric can be thermally excited to the oxide's conduction band edge and escape the SiO_2 [2]. When they are trapped, these electrons are part of the stored negative charge that dictates the e-pot's output voltage. If they all escape to the floating-gate (as shown in Fig. 5 (b)), then they remain part of the stored charge; therefore, the e-pot's state should be minimally affected. On the other hand, any electrons that escape to the tunneling junction are lost to the capacitor and subsequently alter the output voltage of the e-pot. In Fig. 5 (a), (c), and (d), detrapped electrons are less likely to be kept by the floating-gate. The final possible state proposed in the figure is the least desireable: not only are electrons in shallow traps released, but also electrons in deep traps can be released to the tunneling junction and the floating-gate charge is further increased as electrons tunnel off of the gate.

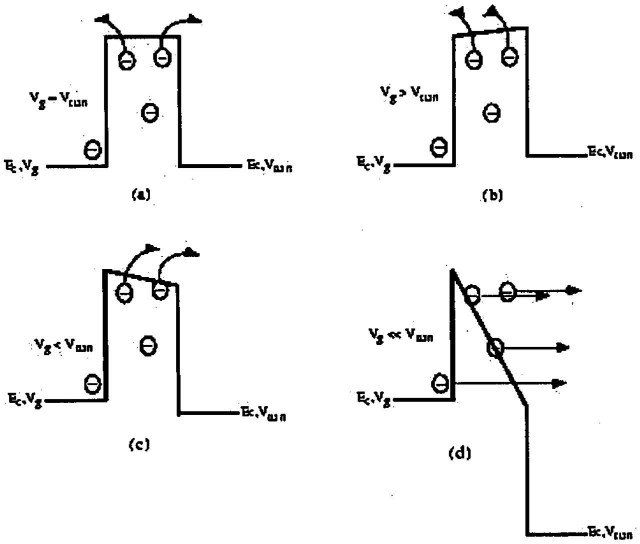


Fig. 5. Electrons in shallow traps in the tunneling oxide (C_{tun} in Fig. 6) may be removed by thermal excitation[2]. If they are removed from the oxide while the e-pot is in a non-programming state, the e-pot's reference value may be adversely affected. (a) No applied oxide voltage. Electrons in shallow oxide traps are equally likely to go to the floating gate or the tunneling junction. (b) Electrons are more likely to go to the gate when it is at a higher voltage than V_{tun}. (c) Electrons are more likely to go to the tunneling junction because it is at a higher voltage than V_g. (d) Thermally exicted electrons are far more likely to go to the tunneling junction. Also, because these conditions are favorable for electron tunneling, electrons tunnel from the floating gate and deep electron traps in the oxide. When it is not being programmed, it is most desirable for an e-pot to be in state (b), because its detrapped electrons are kept on the gate and remain part of the total charge at the capacitance C_{tun}.

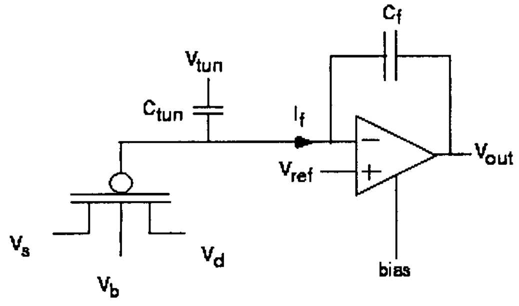


Fig. 6. Consisting of a floating-gate p-channel MOSFET, a tunneling junction, and an op. amp., this structure is used to measure how quickly an e-pot's reference voltage can be changed. Electron tunneling provides a positive I_f through C_{tun} that lowers V_{out}, while hot-electron injection from the drain to the gate of the pFET generates a negative I_f that raises V_{out}.

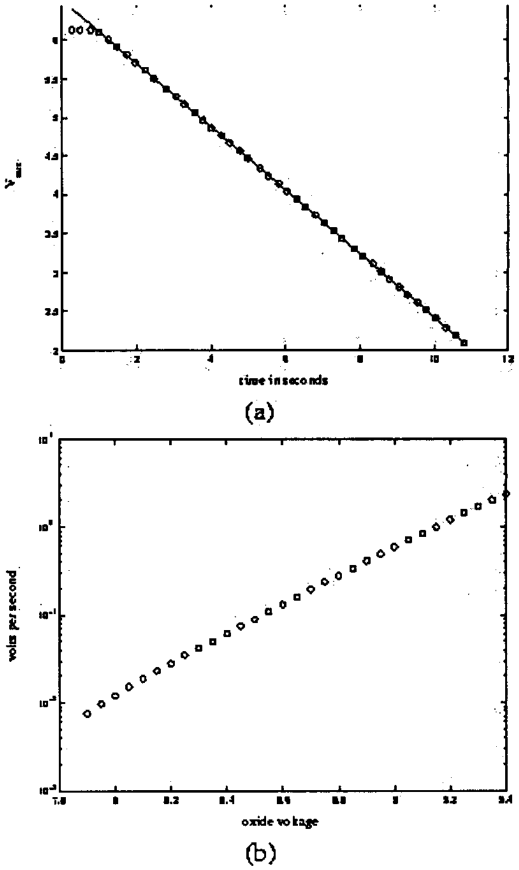


Fig. 7. We measure how quickly electron tunneling can lower V_{out} in Fig. 6. (a) At an applied oxide voltage $V_{tun} - V_{ref} = 8.90V$, a constant tunneling current of $332fA$ results. The tunneling current can be derived from the rate of voltage change, which is $|dV_{out}/dt| = 410mV/s$. (b) We present the rate of reduction of V_{out} as a fuction of V_{ox}, which is the programming rate for lowering an e-pot's voltage.

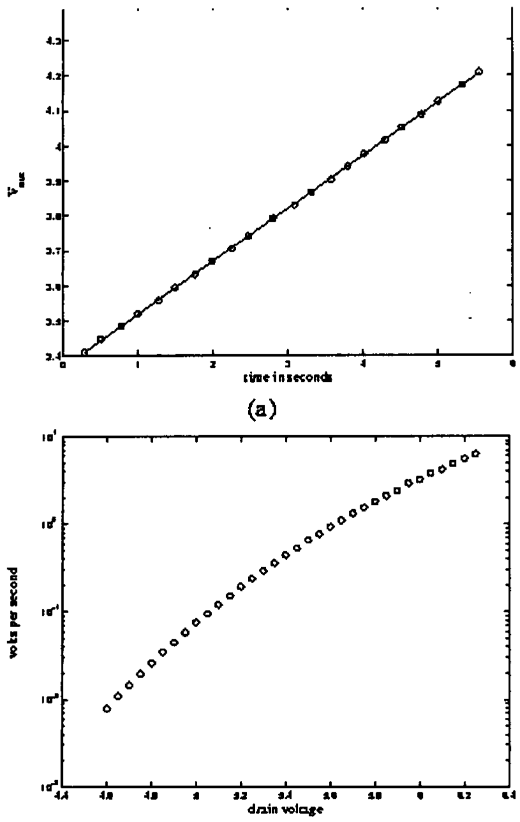
2. PROGRAMMING SPEED

We use the integrating structure in Fig. 6 to test the time necessary to program an e-pot's output voltage. This structure is at the core of the e-pot. The voltage V_{out} is the e-pot's reference voltage. Note the value of the floating-gate voltage is explicitely set by V_{ref}.

When a large voltage is placed across the oxide of the tunneling junction (i.e. $V_{tun} - V_{ref}$ is large), electron tunneling provides a substantial current in the orientation shown as I_f. Assuming an ideal op-amp in Fig. 6, the current I_f flows through the feedback capacitance C_f, and the voltage V_{out} will be the integral of the current:

$$V_{out} = -\frac{1}{C_f}\int I_f(t)\,dt, \qquad (1)$$

where t is elapsed time. As long as $V_{tun} - V_{ref}$ is held



(a)

(b)

Fig. 8. We measure how quickly hot-electron injection can raise V_{out} in Fig. 6. (a) Applying a drain voltage $5.15V$ below V_s and V_b generates a constant injection current of $123fA$. The injection current can be derived from the rate of voltage change, which is $|dV_{out}/dt| = 150mV/s$. (b) Plotting the rate of increase of V_{out} as a fuction of drain voltage, defined as $|V_d - V_s|$, presents the programming rate for raising an e-pot's voltage.

constant, the current will be fairly constant, and (1) can be represented as

$$V_{out} = -\frac{I_f}{C_f}t + V_{out,initial}, \qquad (2)$$

where $V_{out,initial}$ represents an offset voltage due to the initial charge on the floating gate. It is evident that V_{out} falls as a function of the tunneling current. Fig. 7 (a) shows an example of lowering the e-pot's reference voltage at a particular oxide voltage. In Fig. 7 (b), we measure the speeds at which we can lower an e-pot's voltage for a wide range of oxide voltages.

When the drain voltage is much more negative than the source and bulk, then hot-electron injection will provide a substantial current in the direction opposite I_f as it is shown in 6. In this case, V_{out} rises as a function of injection current according to (2), because I_f is negative ($I_{inj} = -I_f$). In voltage is raised for a particular drain voltage. In Fig. 8, we characterize the speeds at which we can raise an e-pot's voltage as a function of drain voltage.

This data was extracted from a $0.5\mu m$ process. It is noteworthy that as process dimensions decrease, the oxide and drain voltages necessary to obtain these programming rates will decrease. Part of our future work on this project is to obtain some of these programming speeds using the structure in Fig. 6 on a $0.25\mu m$ process. We also will further expand our testing to incorporate programming rates. It is worth noting that the highest rates shown in Fig. 7 and 8 are not the fastest that the programming can be accomplished; rather, these ceiling rates are limitations in computer data acquisition which we need to address with a more sophisticated experimental setup.

3. REFERENCES

[1] R. Harrison, J.A. Bragg, P. Hasler, B.A. Minch, and S. Deweerth, "A CMOS Programmable Analog Memory Cell Array using Floating-Gate Circuits," *IEEE Transactions on Circuits and Systems II*, vol. 48, issue 1, Jan. 2001, pp. 4-11.

[2] B. Doyle, "The Hot-Carrier Effect," in *ULSI Devices*, edited by C. Y. Chang and S.M. Sze, John Wiley and Sons, Inc., New York, 2000, pp. 275-332.