

FIXED-CURRENT METHOD FOR PROGRAMMING LARGE FLOATING-GATE ARRAYS

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ABSTRACT

Speed and Accuracy of programming large floating gate array is limited by precision of current measurement and pulse generator. In this paper a novel floating gate programming method is proposed which alleviates the requirement of accurate measurement and facilitates fast programming. As opposed to conventional approaches this method programs fixed value of currents onto the floating gate transistor at variable control gate voltage. The technique is used in conjunction with a coarse programming method, that utilizes the positive feedback nature of pFET injection to improve the speed of programming. Measured results from an array of floating gate cells, fabricated in a $0.5\mu\text{m}$ CMOS process demonstrate the effectiveness of this method to program currents in the order of few picoamperes with approximately 8bits of resolution.

1. INTRODUCTION

Analog EEPROMs are extensively used in design of adaptive systems for long term storage of system parameters [3]. These analog memories are implemented using a floating gate transistor, whose gate is insulated for a standard CMOS process, with silicon-di-oxide. The high quality of the insulator ensures that any charge, injected onto the gate is retained for long interval of time. The charge on the floating gate is modulated by using injection or tunneling and is monitored by measuring the drain current flowing through the corresponding transistor [1]. For the purposes of this paper tunneling will be used as a global erase mechanism and programming is performed only using injection. Speed of programming becomes critical when very small currents have to be programmed using injection on large floating gate arrays. The bottleneck arises due to noise, precision limitations of the measurement devices and the timing of the injection pulse generator. Using on-chip current measurement alleviates the effect of noise and also improves the precision and speed of measurement.

This paper presents an alternative method of programming floating gate cells, where a fixed value of current is programmed on the array but for different values of control

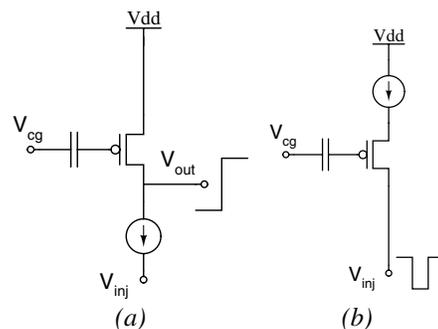


Fig. 1. Floating gate programming procedure (a) Coarse programming: When the current through the cell is close to the programmed value the drain potential V_{out} increases. (b) Fine programming where the source current is fixed and the drain is pulsed to an injection voltage.

gate voltages. This fixed current now can be set to a large value thus improving the speed and accuracy of measurement. In addition the paper uses a coarse-fine programming mechanism, which employs the positive feedback nature of pFET injection for bootstrapping the cell close to the desired value of current.

The paper is organized as follows. Section 2 describes the principle behind coarse-fine programming of floating gate cells. Section 3 describes the parameter estimation procedure for determining the variable control gate voltage for the fixed current. Section 4 analyses the programming procedure and describes some measured characteristics and section 5 concludes with some final remarks.

2. FLOATING GATE PROGRAMMING

The charge on the floating gate can be modified using hot electron injection or through tunneling [2, 1]. Hot electron injection adds electrons to the floating gate and tunneling removes the electrons which changes floating gate voltage and hence the drain current.

For a large array of floating gate cells, and hence speed of programming is critical. Along with speed, the pro-

programming accuracy is also crucial, and has to be performed with a precision of at-least 6 bits for implementing a typical recognition system. To speed up the programming procedure injection has to be performed in two steps (a) coarse programming step, which is aimed to program a coarse current value close to the desired current (b) fine programming step, which is used to incrementally program small values of current and hence to a desired accuracy. The apparatus to perform fast but coarse programming is shown in 1(a) and ensures that at current through the cell is in the neighborhood of desired current. For the purpose of this discussion it is assumed that the drain voltage used for injecting electrons onto the floating gate is V_{pulse} and the current to be programmed onto the floating gate for a drain voltage of $V_{prog} > V_{pulse}$ is I_{pulse} . Also before programming the current through the floating gate cell satisfies $I_{ds} < I_{pulse}$. During coarse programming the V_{out} remains low during the interval as long as $I_{ds} < I_{pulse}$. The Once the drain current exceeds the desired current the output of the comparator flips indicating that the programmed current is in the neighborhood of the desired current I_{pulse} . Under this condition the drain to source potential of the transistor $M1$ drops such that the floating gate cell stops injecting. This procedure is self-stabilizing which guarantees that under very mild conditions the current programmed on the floating gate cell will be an under-estimate of the desired current I_{pulse} . Subsequent injection procedure onto the floating gate is performed using setup 1(b) to perform fine programming to the desired value. The procedure consists of an injection cycle followed by a measurement cycle similar to the method used for programming flash EEPROM [3]. During the injection cycle the source current is fixed to $2I_{pulse}$ and the drain is pulsed to V_{pulse} , which injects electrons onto the floating gate. The constant source current ensures that the injection efficiency is approximately constant during the programming procedure [2]. During the measurement cycle the source is connected to a fixed potential and the drain current is measured at V_{prog} . Programming stops when the measured drain current exceeds the desired value I_{pulse} . Figure 1 shows the state of the floating gate cells after injection where all the cells have been programmed to a fixed current value of $10nA$.

Using the coarse and fine programming methods a floating gate cell can be programmed to a desired current value by either

1. Programming the desired current at a particular value of the control gate voltage.
2. Interpolative method of programming a fixed current at an operating point obtained using a I_{ds} vs V_{cg} characteristic.

The first method of programming is the most popular procedure used for programming floating gates. An on-chip

current measurement is required during the measurement cycle to detect the completion of programming. One of the drawback of this procedure is that the precision of programming is limited by duration of injection pulses which influences the programming speed. Therefore programming very small currents programming, requires very fine pulses and hence a large programming duration. The use of this procedure therefore is limited to small size arrays.

The second alternative is attractive when a large array of floating gates is required to be programmed with a reasonable accuracy. Programming a fixed current eliminates the use of sophisticated current measurement and a speed up in programming by using coarse and fine programming method. The algorithm used to program a floating gate cell using the coarse-fine method is described as follows:

1. Let the target current to be programmed on a floating gate cell be I_{prog} at a desired control gate voltage V_{cg}
2. Required is a programmable voltage source with > 12 bits precision. and a current measurement instrument to measure a fixed value of current.
3. The initial condition of the cell is that the drain current through the floating gate cell I_{ds} is less than the desired current I_{prog} .
4. Compute the floating gate transfer characteristic $I_{ds}(V_{cg})$.
5. Using the model obtain the incremental voltage ΔV by which the transfer characteristic needs to be translated such that the current at $I_{ds}(V_{cg} + \Delta V) = I_{prog}$.
6. Obtain V_{prog} such that $I_{ds}(V_{prog}) = I_{fixed}$.
7. Set the control gate voltage to $V_{prog} + \Delta V$ and program I_{fixed} using the coarse-fine programming procedure.

The success of the programming algorithm depends on two factors:

1. The control voltage of the floating gate cell can be set with a resolution of atleast 12bits. Such voltage biases are readily available with commercial data acquisition cards.
2. A reliable transistor model is available that can accurately interpolate between the above threshold operation and sub-threshold operation. Several analytical models for MOS transistor operation are available like ACM [4] and EKV [5] model which approximates the characteristic of the MOS transistor.

3. EKV MODEL ESTIMATION

A variant of a simple EKV model [5] is used to obtain the transfer characteristic $I_{ds}(V_{cg})$ of MOS transistor. The current through the MOS transistor can be expressed as the difference between forward I_F and reverse components I_R as

$$I_{ds} = I_o(I_F - I_R) \quad (1)$$

where

$$I_F = \log^2(1 + e^{\kappa(V_g - V_{To}) - V_s}) \quad (2)$$

$$I_R = \log^2(1 + e^{\kappa(V_g - V_{To}) - V_d}) \quad (3)$$

Under saturation condition $I_F \gg I_R$, the model is simplified to

$$I_{ds} = a^2 \log^2(1 + e^{bV_{cg} + c}) \quad (4)$$

with parameters a , b and c . The parameters of the model (4) can be estimated using a simple iterative regression algorithm described below.

1. Required is a measured characteristic of drain current I_{ds} vs the control voltage V_{cg} . Ensure $V_s = V_{dd}$ and $V_d = 1V$.
2. Start with a rough initial estimate of $b = b^1$. This initial estimate can be obtained by regressing the subthreshold region current with the input voltage where $b^1 = \frac{\delta \log I_d}{2\delta V_{fg}}$.
3. Using this initial estimate of b^1 obtain the estimate of $a = a^1$ by regressing the above threshold current to obtain $a = \frac{1}{b^1} \frac{\partial \sqrt{I_d}}{\partial V_{fg}}$.
4. Let $R_o = \log[\exp(\frac{\sqrt{I_{ds}}}{a^1}) - 1]$, then estimate the value of c is the intercept obtained by regressing R_o with V_{fg} . The new better estimate of b is obtained as $b = \frac{\partial R_o}{\partial V_{fg}}$.
5. a , b , c are the desired parameters of the model.

Figure 2(a)-(b) shows the comparison of empirical data obtained from a floating gate cell with the model given by (4) and parameters obtained by the EKV algorithm. It can be readily verified that equation (4) along with parameters obtained using EKV algorithm models the floating gate cell characteristic accurately.

4. ANALYSIS AND RESULTS

It can be shown that using the fixed-current method very small currents can be programmed onto floating gate cells with a reasonable accuracy.

Let the target above threshold current to be programmed on this floating gate is I_{ds}^* and the error in programming is

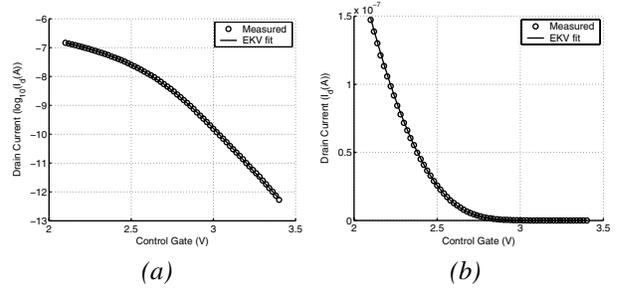


Fig. 2. Comparison of the measured and empirical EKV characteristic for a floating gate cell (a) subthreshold characteristic (b) above threshold characteristic.

given by δI_{ds} and the corresponding error on the floating gate voltage referred to the control gate is δV_{fg} . Therefore

$$(I_{ds}^* + \delta I_{ds})^{1/2} = a \log(1 + \exp[b(V_{fg}^* + \delta V_{fg}) + c]) \quad (5)$$

Using the above threshold square voltage law and the first order approximation with $\delta I_{ds}/I_{ds}^* \ll 1$ the following is obtained

$$V_{fg}^* + \delta V_{fg} = \frac{I_{ds}^{*1/2}}{ab} \left(1 + \frac{1}{2} \frac{\delta I_{ds}}{I_{ds}^*}\right) \quad (6)$$

$$\delta V_{fg} = \frac{\delta I_{ds}}{2abI_{ds}^{*1/2}} \quad (7)$$

When error in the floating gate voltage δV_{fg} is translated to the subthreshold operation the following expressions are obtained

$$I_{ds}^p + \delta I_{ds}^p = a^2 \exp[2b(V_{fg}^p + \delta V_{fg}) + c] \quad (8)$$

$$\delta I_{ds}^p = I_{ds}^p (\exp[2b\delta V_{fg}] - 1) \quad (9)$$

$$= I_{ds}^p \left[\exp\left(\frac{\delta I_{ds}}{aI_{ds}^{*1/2}}\right) - 1 \right] \quad (10)$$

Using the fact $\delta I_{ds}/I_{ds}^{*1/2} \ll 1$ and Taylor series expansion of the $\exp(\cdot)$ function the error in programming a small subthreshold current on the floating gate is given by

$$\delta I_{ds}^p = \frac{\delta I_{ds}}{aI_{ds}^{*1/2}} I_{ds}^p \quad (11)$$

If we insert typical values of parameters $a = 10^{-4}$, $I_{ds} = 40nA$, $\delta I_{ds} = 2nA$ in equation (11) the final error in programming a sub-threshold current is found to be 0.01% which is more than sufficient for the precision required for our application.

An array of 180×160 floating gate transistors has integrated into a pattern recognizer [6], a micrograph of which is shown in Figure 3. Each floating gate transistor of the

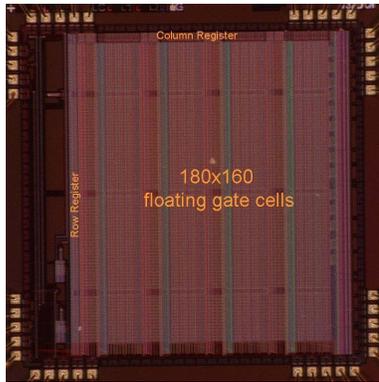


Fig. 3. Micrograph of an array of floating gate cells implemented as a matrix vector multiplier.

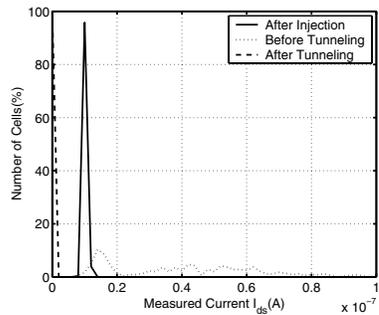


Fig. 4. Histogram of drain currents through the floating gate cell before tunneling (erase), after tunneling (erase) and after programming a fixed current using injection.

MVM is addressable using a shift register, facilitating its programming and measurement.

Before programming the floating gate array all the cells are programmed to a fixed current a fixed control gate voltage. This achieved through tunneling and a subsequent coarse-fine injection based programming method. Figure 4 shows a histogram of the drain current flowing through the cells before tunneling, after tunneling and after injection. Measured characteristics indicate that the subthreshold slope of the floating gate transistors in the array are well matched and their mismatch can be effectively modeled by the mismatch in their threshold voltage.

To demonstrate the programming accuracy of the coarse-fine technique, 64 random floating gate cells were chosen and programmed at an increment of 10pA . Figure 5 shows a plot of 64 different floating gate cells and the their measured drain currents, which demonstrates a programming accuracy of more than 7 bits.

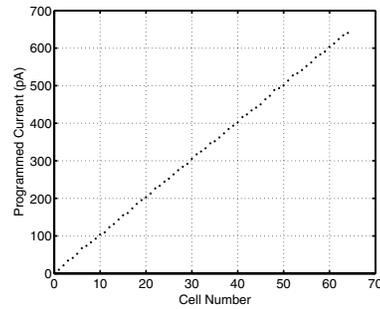


Fig. 5. Plot of currents programmed on 64 different floating gate cells using coarse-fine programming at an increment of 10pA .

5. CONCLUSIONS

This paper introduced a novel floating gate programming method based on coarse-fine programming technique. By programming a fixed value of current, the method alleviates the problem of noise and precision induced by measurement equipments. Using this technique very small currents can be rapidly programmed on large floating gate arrays making it a suitable choice for configuring ultra-low power analog systems.

6. REFERENCES

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