THE TEMPERATURE SENSITIVITY OF A BISTABLE RAM

A Thesis
by
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THE TEMPERATURE SENSITIVITY OF A BISTABLE RAM

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ABSTRACT

The Temperature Sensitivity of
A Bistable RAM. (May 1986)

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Lu's Modified Trapping Model is applied to the polycrystalline-silicon resistor of a new bistable RAM cell. The effect of temperature on the resistor is explored with respect to the operation of the RAM cell's refresh mechanism. A temperature range of 0—100°C is investigated. The results are analyzed as the grain size, doping concentration, and length of the resistor are varied. The author concludes that for the test geometries specified by Çilingiroğlu, the creator of the bistable RAM, the RAM cell will fail to operate correctly over a temperature range of 0—100°C. An optimization procedure is suggested to adjust the original parameters of the cell so that an operating temperature range 0—100°C may be achieved.
To my parents
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CHAPTER 1

INTRODUCTION

The search for small, dense memories has led to the dynamic RAM cell which is comprised of one transistor and one capacitor. Unfortunately the refresh circuitry associated with dynamic RAM's is complex, often making them unsuitable for circuits integrating memory and logic. Static RAM is the current solution to this problem.

In [1-4] Çilingiroğlu has proposed an alternative to static RAM he calls the bistable RAM. This cell employs a charge pump to refresh the dynamically stored information and thus simultaneously avoids the large cell size of a static RAM while eliminating the complex refresh circuitry needed with the dynamic RAM.

Because of the refresh mechanism used the cell is sensitive to temperature and may fail to operate at temperatures extremes. It is the purpose of this research to specify the polysilicon resistor to be used in the cell so that the cell operates for temperatures between 0 - 100°C.

So that the reader may fully appreciate the problem a review of the literature will be given. First the charge pump will be explained, and then the physics of the bistable cell will be analyzed. The modified trapping model which describes the behavior of the polysilicon resistor will be discussed in Chapter 3. In Chapter 4 the resistor specifications will be given, and Chapter 5 will present an analysis of the results and some conclusions.

Journal model is IEEE Journal of Solid-State Circuits.
CHAPTER II

LITERATURE REVIEW

A. CHARGE PUMPING

Brugler and Jespers in [5] provide a basic explanation of charge pumping. A brief summary of that explanation follows.

Consider Figure 1. Before the gate pulse is applied, \( V_g = V_{rb} \) and \( I_b \) is positive and equal to the reverse bias leakage current of the transistor. When \( V_g \) falls to \( V_{rp} \), Figure 2, the n region under the gate is temporarily driven into deep depletion and the potential barrier between the n and p regions is lowered. Holes from the p regions rush under the gate of the transistor to restore equilibrium. When the pulse is removed \( V_g \) returns to \( V_{rb} \). As \( V_g \) rises the misplaced charge under the gate attempts to return to the p regions. When \( V_g = V_{rb} \), where \( V_{rb} > V_{fb} \), any charge that failed to reach the p regions recombines in the substrate (Figure 3). \( V_{fb} \) is the flat-band voltage. This charge results in the pumping current \( I_p \). The trapped charge density, \( Q_{trap} \), per gate pulse is

\[
Q_{trap} = \alpha Q_{free} + qN_{st}
\]

where \( Q_{free} \) is the free charge hole density in the inversion layer \( (cm^{-2}) \), \( \alpha \) is the fraction of free carriers which recombine in the bulk and \( N_{st} \) is the total fast surface-state density \( (cm^{-2}) \) which contributes to the effect.

When \( V_g > V_s + V_t \), where \( V_s \) is the voltage applied to the p regions and \( V_t \) the threshold voltage, the surface is depleted and \( Q_{free} \sim 0 \). When \( V_g < V_s + V_t \) the surface is in strong inversion and

\[
Q_{free} = -C_{ox}(V_g - V_s - V_t)
\]
where $C_{ox}$ is the oxide capacitance per unit area. Therefore the pumping current is given by

$$I_p = A_g f (\alpha C_{ox} (V_g - V_s - V_t) + qN_{st})$$

where $A_g$ is the area of the gate and $f$ is the pulse repetition frequency. This equation describes a phenomenon where during each gate pulse a quantity of charge is measured out under the gate and then pumped into the substrate.

The first term in (3) considers the effect of device geometry on $I_p$ and is labeled

\[ \text{Vs} \]
the "geometric component" by Brugler and Jespers. The polysilicon gate of the transistor and the n type substrate can be modeled as the parallel plates of a capacitor which are separated by a dielectric. When a gate pulse is applied holes are stored on the lower plate of this capacitor. These holes are free mobile carriers. For a slowly varying gate voltage the holes will have time to reach the junction before the inversion layer is removed. If $V_g$ rises quickly more of the holes will fail to reach the junction, recombine in the bulk, and $\alpha$ will increase.

Fig. 2 The charge pump for $V_g < V_f + V_t$. 
Fig. 3 The charge pump for $V_g = V_{rb}$.

The second term, "the surface-state component," explains the relationship between the pumping current and the surface-state density. Charge trapped in the surface states under the gate is always lost when the inversion layer is removed. To a first order approximation the surface-state density is given by

$$N_{st} = N_t (\phi_0 - \phi_s)$$  \hspace{1cm} (4)

where $N_t$ is the trap density, $\phi_0$ the surface potential with zero gate voltage, and $\phi_s$ the surface-state potential with a negative gate voltage.
Therefore if the gate voltage is varied slowly, $\alpha$ will be small, and the amount of pumped charge can be controlled by altering the trap density, a processing step, or by controlling the surface potential.

B. THE PHYSICS OF THE BISTABLE RAM CELL

The material contained in this section was drawn from [1-4,6]. The configuration of the bistable RAM cell under consideration is shown in Figure 4. Figure 5 is a simpler drawing of the cell. Other configurations may be found in [1-3]. A pmos process is assumed although the results of this research may be applied to nmos. The storage gate potential is fixed at $V_{rp}$ and the doping profiles beneath the pumping gate and storage gate are identical.

When a constant negative dc voltage is applied to the storage gate a potential well, the storage well, is formed. The storage well is accessed via the wordline transistor. Two states may then be defined: the full state when the storage well is full of holes, and the empty state when the storage well is empty.

When the well is in the empty state, holes from the substrate will leak into the well gradually filling the well. Therefore, a refresh mechanism must be supplied that will maintain the empty state. The refresh mechanism employed is Brugler and Jespers' charge pump.

First consider the empty state. When $V_g = V_{rp}$ the depth of the pump well and the storage well will be equal. When the refresh signal, $V_r$, returns to $V_{rb}$, $V_g$ will begin to rise. The rate at which $V_g$ rises is determined by the value of $R$ and the capacitance of the pumping gate. Because the well is empty, the surface is deeply depleted, the gate capacitance is small, and thus $V_g$ rises quickly. $V_{gz}$ is the pump gate voltage for which the surface enters weak accumulation. When $V_g = V_{gz}$,
electrons annihilate the holes trapped in the surface states and the pumping current begins to flow. Therefore during a refresh period in which $V_y$ is allowed to rise to $V_{gx}$ any charge trapped in the interface state traps will be pumped into the substrate. If the number of traps is greater than the number of holes leaking into the well during one refresh period, $T = T_B + T_P$, where $T_P$ is the length of time $V_r = V_{rh}$, the peak level, and $T_B$ the length of time $V_r = V_{rb}$, the base level, the empty state will be maintained.

Without the charge pump, the full state is stable. However if the charge pump is allowed to operate in the full state the pump will gradually empty the storage well. Therefore during the full state the charge pump must be disabled.

When the cell is in the full state and $V_y = V_{rp}$ the charge stored in the storage well will flow into the pump well until the pump and storage well surface potentials
are equal. When $V_r$ returns to $V_{rb}$, $V_g$ will begin to rise. However because the pump well contains charge, the surface is not in deep depletion as in the empty state but rather in strong inversion. Therefore the gate capacitance will be large and the rate at which $V_g$ rises to $V_{gz}$ will be slow.

The full state and empty state waveforms are shown in Figure 6. For the cell to operate correctly, pumping charge in the empty state and inhibiting pumping in the full state, $T_B$ must be greater than or equal to $T_{empty}$ and less than $T_{full}$. So two constraints for proper operation have been identified: $I_p \geq I_L$, the pumping current must be greater than the leakage current, and $T_{empty} \leq T_B \leq T_{full}$.

Now let us analyze the cell for an arbitrary initial storage surface potential $\phi_{ss}(0)$. The following analysis follows [6]. From MOS theory the charge on the pump gate, $Q_y$, is given by

$$Q_y = A_pC_{ox}(V_g - \phi_{sp} - \phi_{ms})$$  

(5)

where $A_p$ is the area of the pump gate, $\phi_{sp}$, the pump surface potential, and $\phi_{ms}$
the work function difference. Differentiating (5) with respect to time yields

\[ I = A_p C_{ox} \frac{dV_g}{dt} (1 - \frac{d\phi_{sp}}{dV_g}). \]  

(6)

The gate voltage may be related to the pump surface potential and the amount of
charge stored in the pump well, $Q_p$, by

$$ V_g = V_{fb} + \phi_{sp} - V_o^{1/2}(-\phi_{sp})^{1/2} - Q_p/A_pC_{ox} \quad (7) $$

where $V_{fb}$ is the flat-band voltage and $V_o$ the body-factor. Similarly, the storage surface potential, $\phi_{ss}$, may be related to the amount of charge in the storage well, $Q_s$, by

$$ V_{sp} = V_{fb} + \phi_{ss} - V_o^{1/2}(-\phi_{ss})^{1/2} - Q_s/A_sC_{ox} \quad (8) $$

where $A_s$ is the area of the storage gate.

Now consider Figure 7. When $V_g = V_{rp}$, charge stored in the storage well flows into the pump well until the storage and pump well surface potentials are equal. So, at $t = t_0$, $V_g = V_{rp}$ and $\phi_{sp}(0) = \phi_{ss}(0)$. At $t = t_{0+}$, $V_g$ is switched to $V_{fb}$ and $\phi_{sp}$ begins to rise. As $\phi_{sp}$ increases toward zero the charge stored in the pump well flows back into the storage well keeping the two surface potentials equal. While the pump well contains charge the capacitance of the well will be large and $\phi_{sp}$ will rise slowly. At some time, $t = t_1$ (Figure 8), all of the stored charge has been returned to the storage well, $\phi_{sp} = \phi_{ss}$, $Q_p = 0$, and $Q_s = Q_{total}$, where $Q_{total}$ is the total amount of stored charge. During time $t_1 \leq t < t_2$ the storage surface potential remains approximately constant. The pump surface potential rises quickly because $Q_p = 0$ and the pump capacitance has been reduced. At $t = t_2$, $\phi_{sp} = \phi_f$ and $V_g = V_{gx}$. As $V_g$ rises above $V_{gx}$ the surface enters weak accumulation, electrons begin to annihilate the holes trapped in the fast surface states and the pumping current begins to flow.

So, two time intervals have been identified. During $t_0 \leq t < t_1$, $Q_p \neq 0$ and $\phi_{sp} = \phi_{ss}$. During $t_1 \leq t < t_2$, $Q_p = 0$. At $t = t_2$, $\phi_{sp} = \phi_f$ and charge pumping is initiated.
Fig. 7  $Q_p$ and $Q_s$ for an arbitrary $\phi_s(0)$ at $t = t_0$.

Fig. 8  $Q_p$ and $Q_s$ for an arbitrary $\phi_s(0)$ at $t = t_1$. 
Now consider the time interval \( t_0 \leq t < t_1 \). If the cell is not accessed the total stored charge, \( Q_{\text{total}} \), remains constant. From (7) and (8) \( Q_{\text{total}} \) is given by

\[
Q_{\text{total}} = -C_{oz}(A_p V_g + A_s V_{rp}) + C_{oz}(A_p + A_s)(V_{fb} + \phi_{sp} - V_o^{1/2}(-\phi_{sp})^{1/2}).
\]  

Differentiating (9) with respect to time yields

\[
0 = -A_p + (A_p + A_s)
\left( \frac{d\phi_{sp}}{dV_g} + \frac{V_o^{1/2}}{2(-\phi_{sp})^{1/2}} \frac{d\phi_{sp}}{dV_g} \right).
\]  

Rearranging (10) produces

\[
\frac{d\phi_{sp}}{dV_g} = \frac{A_p}{(A_p + A_s)(1 + V_o^{1/2}/2(-\phi_{sp})^{1/2})}.
\]  

Substituting (11) into (6) yields the differential equation

\[
l = A_p C_{oz} \frac{dV_g}{dt} \left( 1 - \frac{A_p}{(A_p + A_s)(1 + V_o^{1/2}/2(-\phi_{sp})^{1/2})} \right).
\]  

\( \phi_{sp}(0) \) is close to \( \phi_{sp}(t_1) \) and \( V_o^{1/2}/2(-\phi_{sp})^{1/2} \) is small. Therefore \( \phi_{sp} \) in (12) may be approximated by \( \phi_{sp}(0) \) which yields

\[
l = A_p C_{oz} \frac{dV_g}{dt} \left( 1 - \frac{A_p}{(A_p + A_s)(1 + V_o^{1/2}/2(-\phi_{sp}(0))^{1/2})} \right).
\]  

If a full state is written while the pump well is in deep depletion both the pump well and the storage well will be filled with holes. When \( V_r \) is switched to \( V_{rb} \) the pump surface potential will begin to rise and charge will spill into the substrate. This charge, unlike the charge which leaks into the well during the empty state, did not originate in the substrate and therefore may flood the surrounding cells and destroy information. So, it is necessary to control the amount of charge written to a cell.
To prevent spillage, the storage well surface potential must never exceed \( \phi_f \), the surface potential at which accumulation begins. Thus if a small safety margin is employed \( \phi_{sa} \) must remain \( \leq 2\phi_f \). \( \phi_{sa} \) reaches a maximum at \( t = t_1 \). So at \( t = t_1 \), letting \( \phi_{sa}(\text{max}) = 2\phi_f \), yields

\[
Q_{\text{total}}(\text{max}) = -A_s C_{Ox} \left\{ V_{rp} - V_{fb} - 2\phi_f + V_o^{1/2}(-2\phi_f)^{1/2} \right\}
\]

(14)

from (8) where \( Q_s = Q_{\text{total}} = Q_{\text{total}}(\text{max}) \).

At \( t = t_0 \), \( V_g = V_{rp} \), \( \phi_{sp}(0) = \phi_{sa}(0) \) and using (9)

\[
Q_{\text{total}} = C_{Ox}(A_p + A_s) \left\{ -V_{rp} + V_{fb} + \phi_{sp}(0) - V_o^{1/2}(-\phi_{sp}(0))^{1/2} \right\}.
\]

(15)

The maximum value of \( \phi_{sp}(0) \) can then be found by substituting \( Q_{\text{total}}(\text{max}) \) in (14) for \( Q_{\text{total}} \) in (15). Doing this and solving yields

\[
\phi_{sp}(0)(\text{max}) = -\frac{1}{4} \left\{ -V_o^{1/2} + \sqrt{V_o - 4 \left( \frac{Q_{\text{total}}(\text{max})}{C_{Ox}(A_p + A_s)} + V_{rp} - V_{fb} \right)} \right\}^2.
\]

(16)

So, when a full state is written, charge will be allowed to fill the cell until \( \phi_{sa} = \phi_{sp}(0)(\text{max}) \). Then if the pump well is in deep depletion when a full state is written (e.g. \( V_g = V_{rp} \)), \( \phi_{sa}(t_1) = \phi_{sp}(t_1) = 2\phi_f \) and spillage will be prevented. Because refreshing is asynchronous with respect to read/write operations, a full state could be written while \( V_g \geq V_{gx} \). If this happened only the storage well would be filled, the total amount of stored charge would be a minimum, \( \phi_{sa}(t_1) = \phi_{sp}(0)(\text{max}) \) and from (8)

\[
Q_{\text{total}}(\text{min}) = -A_s C_{Ox} \left\{ V_{rp} - V_{fb} - \phi_{sp}(0)(\text{max}) + V_o^{1/2}(-\phi_{sp}(0)(\text{max}))^{1/2} \right\}.
\]

(17)

Then when \( V_g \) returned to \( V_{rp} \), \( \phi_{sp}(0)(\text{min}) \) would be

\[
\phi_{sp}(0)(\text{min}) = -\frac{1}{4} \left\{ -V_o^{1/2} + \sqrt{V_o - 4 \left( \frac{Q_{\text{total}}(\text{min})}{C_{Ox}(A_p + A_s)} + V_{rp} - V_{fb} \right)} \right\}^2.
\]

(18)
Recall that (12) was approximated by (13) by letting $\phi_{sp} = \phi_{sp}(0)$ since the total range of values for $\phi_{sp}$ was small. The use of $\phi_{sp}(0)(\text{min})$ in (13) will produce a conservative (the shortest) estimate of the time from $t_0$ to $t_1$ when the cell is in the full state.

Now consider the time interval $t_1 \leq t < t_2$. In this interval $d\phi_{sp}/dV_g$ is approximately constant. Letting $d\phi_{sp}/dV_g = H$ gives from (6)

$$I = A_p C_{oz}(1 - H)\frac{dV_g}{dt}.$$  \hspace{1cm} (19)

So four governing equations have now been identified:

$$I_p \geq I_L,$$  \hspace{1cm} (20)

$$T_{empty} \leq T_B \leq T_{full},$$  \hspace{1cm} (21)

$$I = A_p C_{oz} \frac{dV_g}{dt} (1 - \frac{A_p}{(A_p + A_s)(1 + V_0^{1/2}/2(-\phi_{sp}(0))^{1/2})})$$  \hspace{1cm} (22)

for $t_0 \leq t < t_1$ and

$$I = A_p C_{oz}(1 - H)\frac{dV_g}{dt}$$  \hspace{1cm} (23)

for $t_1 \leq t < t_2$. \\
\hspace{1cm}
CHAPTER III

THE MODIFIED TRAPPING MODEL

In [7] Lu proposes two models for polysilicon passive devices, the modified trapping model which considers only thermionic emission and which clarifies and extends the work of Seto [8], Baccarani et al. [9], Tarng [10] and others, and the TE+TFE+TFES model which includes the combined effects of thermionic emission, thermionic field emission, and scattering at the grain boundaries. The modified trapping model was used in this research instead of the TE+TFE+TFES model for the two reasons outlined below.

Thermionic emission (TE) is based on the classical premise that only carriers with energy greater than \( qV_B \) can surmount a potential barrier of height \( V_B \). This idea has been modified by quantum mechanics, where carriers with energy \( < qV_B \) can tunnel through potential barriers and where some carriers with energy \( > qV_B \) will be reflected. This quantum mechanical transport mechanism is thermionic field emission (TFE). Lu in [7] calculates the ratio of TFE current to TE current. This ratio is plotted against temperature in Figure 9. For temperatures \( \geq 0^\circ C \) this ratio is \( < 1 \) and TE is the dominate transport mechanism.

The second reason the modified trapping model was chosen, was that although the TE+TFE+TFES model is more accurate, especially at low temperatures, it requires that four physical parameters \( e_t, Q_t, \chi \) and \( \delta \) be known. \( e_t \) is the trapping state energy of the grain boundary traps, \( Q_t \) is the grain boundary trapping state density, \( \chi \) is the grain boundary potential barrier height above \( V_B \), and \( \delta \) is the grain boundary potential barrier width. The modified trapping model requires a knowledge of only \( e_t \) and \( Q_t \). Because the modified trapping model has been studied by others, approximate values for \( e_t \) and \( Q_t \) can be found in the literature. Seto
[8] gives $Q_t \sim 3.34 \times 10^{12}$ and $e_t \sim -.18$ for a grain size $L = 230\text{Å}$. Lu's data, [7], yields $Q_t \sim 1.9 \times 10^{12}$ and $e_t \sim -.17$ for $L = 1220\text{Å}$. Values for $\chi$ and $\delta$ must either be obtained from only Lu's work or from actual measurements. Since such measurements were not available to the author, and since thermionic emission is still the dominate conduction process even at $0^\circ\text{C}$ the modified trapping model was used.

The following development of the transport equation is drawn from [7].

Each grain (crystallite) is considered to be a rectangle of width $L$ and cross-
Fig. 10 Modified polysilicon trapping model. 
From Lu [7].
sectional area A. Such a crystallite is shown in Figure 10a. One dimensional transport through the crystallite is assumed. The edge (boundary) of the crystallite has a random structure which leads to the formation of trapping states. However the center of the crystallite is composed of ordered atoms and may be considered single crystal material. When the polysilicon film is doped an impurity level is formed inside the crystallites, and impurity atoms are ionized to create majority mobile carriers. These carriers are trapped in the grain boundary trapping states, depleting the crystallite and forming a potential barrier at the grain boundary. The energy-band diagram is shown in Figure 10b (p. 16). \( E_1 \), the intrinsic Fermi level, is the zero reference. Using the depletion approximation and Poisson's equation the potential barrier height can be derived as

\[
V_B = \frac{qNW^2}{2\varepsilon}
\]

(24)

where \( N \) is the doping concentration, \( W \) the depletion region width, and \( \varepsilon \) the permittivity of silicon.

There exists a doping concentration \( N* \) at which all of the available traps have been filled. For \( N < N* \) the width of the depletion region extends throughout the crystallite and \( 2W = L \). For \( N > N* \), \( 2W < L \) and the crystallite is no longer completely depleted.

Lu calculates \( N* \) by first finding the effective trapping state density \( Q_t^* \), which is related to \( Q_t \), the number of metallurgical traps per cm² by

\[
Q_t^* = \frac{Q_t}{1 + 2\exp[(E_F - e_t + qV_B)/kT]}
\]

(25)

where \( k \) is Boltzmann's constant, \( T \) absolute temperature and \( E_F \) the Fermi level. So, when \( N < N* \) the Fermi level is pinned by the grain boundary trapping states.
At the center of the grain, the hole concentration $p(0)$ is given by

$$p(0) = n_i \exp(-E_F/kT)$$  \hspace{1cm} (26)$$

where $n_i$ is the intrinsic carrier concentration given as

$$n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2}(m_e^* m_h^*)^{3/4} \exp(-E_g/2kT)$$  \hspace{1cm} (27)$$

where $h$ is Planck's constant, $m_e^*$ is the conductivity effective mass of holes, $m_h^*$ the conductivity effective mass of electrons, and $E_g$ the band gap energy of silicon.

When $N = N^*$ all available traps have been filled and $p(0) = N^*$. Therefore if $Q_t^*$ is equated to the number of ionized dopants in the depletion region, $Q_t^* = N2W$, (25) and (26) can be combined to yield

$$N^* = \frac{Q_t}{L} - 2n_i \exp(-e_t/kT) \exp(q^2 N^* L^2/8\varepsilon kT)$$  \hspace{1cm} (28)$$

which can be iteratively solved for $N^*$.

A. CALCULATING THE CURRENT DENSITY FOR $N < N^*$

The transport equation is

$$J_B = 2qp(0)\left(\frac{kT}{2\pi m_h^*}\right)^{1/2} \exp\left(-\frac{qV_B}{kT}\right) \sinh\left(\frac{qV_{ba}}{2kT}\right)$$  \hspace{1cm} (29)$$

where $V_{ba}$ is the voltage which drops across a single barrier.

When $N < N^*$ each grain is totally depleted and $V_{ba}$ equals $V_a/N_g$ where $V_a$ is the applied voltage and $N_g$ is the number of grains. $V_B$ can be found by substituting $W = L/2$ in (24). $E_F$ can be found from (25) by equating $Q_t^*$ and $2NW$, as

$$E_F = e_t - qV_B + kT \ln(1/2(\frac{Q_t}{L N} - 1)).$$  \hspace{1cm} (30)$$

$p(0)$ can then be calculated using (26). Following this procedure $J_B$ can be determined.
B. CALCULATING THE CURRENT DENSITY FOR $N > N^*$

When $N > N^*$ the crystallite contains both depleted and neutral regions. Dopant atoms in the neutral region are ionized to an impurity concentration $N^+$ given by

$$N^+ = \frac{N}{1 + 2 \exp[(E_A - E_F)/kT]}$$

(31)

where $E_A$ is the acceptor impurity level. In the neutral region $p(0) = N^+$ so equating (31) and (26) yields

$$ni \exp(-E_F/kT) = \frac{N}{1 + 2 \exp[(E_A - E_F)/kT]}$$

(32)

which can be iteratively solved for $E_F$ and $p(0)$. $W$ can be then be found from (25) to be

$$W = \frac{Q_t}{2N[1 + 2(ni/N^+ \exp(-e_t/kT) \exp(q^2NW^2/2ekT)]}.$$  

(33)

Once $W$ is known $V_B$ can also be determined.

Now refer to Figure 10c (p. 16). Since the resistivity of single crystal silicon is much smaller than the barrier resistivity, it can be neglected when $W$ is large. But as $N$ increases above $N^*$, $W$ becomes small and the crystallite resistivity, $\rho_c$, becomes significant. $\rho_c$ may be approximated by

$$\rho_c = \frac{1}{q\mu_h p(0)}$$

(34)

where $\mu_h$ is the hole mobility [11].

At 300°K, $\mu_h$ may be approximated by

$$\mu_h = 47.7 \pm (495.0 - 47.7)/(1 + \frac{p(0)}{6.3 \times 10^{16}})^{75}$$  

(35)

which is temperature independent [12]. Since $\rho_c$ becomes significant only for large doping concentrations and since the temperature sensitivity of $\mu_h$ decreases as $N$ increases, the error introduced by (35) will be small.
In [7] the voltage which drops across the crystallite bulk, \( V_c \), is given as

\[
V_c = J_c(L - 2W)\rho_c.
\]  
(36)

Since \( V_c + V_{ba} = V_a/N_q \) and since \( J_c = J_B \), (29) and (36) can be simultaneously solved with an iterative numerical procedure.

C. THE SENSITIVITY OF RESISTIVITY TO DOPING CONCENTRATION

First let us analyze the behavior of \( \rho \), the resistivity, as \( N \) is increased to \( N^* \). \( p(0) \) will increase as \( N \) increases because the Fermi level moves toward the valence band as the boundary layer traps become filled. Since \( W \) is a constant, \( V_B \propto N \). So, at a given temperature the transport equation will be dominated by two competing terms, \( p(0) \) and \( V_B \). \( p(0) \) will tend to increase \( J_B \) as \( N \) increases and \( V_B \), because it contributes to a negative exponential, will tend to decrease \( J_B \). \( p(0) \) wins the battle. Therefore the resistivity will gradually decrease as \( N \) increases toward \( N^* \).

Now let us examine how the TCR, the temperature coefficient of resistance, varies as the doping concentration increases above \( N^* \). From (26), it can be seen that as the doping concentration increases and \( E_F \) moves toward the valence band, \( p(0) \) will increase. Physically this means that since the boundary layer traps have been filled, any additional ionized carriers are free to conduct. From (33), it can be seen that the depletion region width decreases as \( N \) increases. The depletion width shrinks because the number of dopant atoms within the depleted region must remain equal to the number of available traps. Thus as the number of dopant atoms per \( \text{cm}^3 \) increases the depletion layer width must decrease. As \( W \) shrinks the potential barrier height will also fall. So whereas \( p(0) \) and \( V_B \) fought against one another in the transport equation when \( N < N^* \) they now work together to increase \( J_B \) and
reduce the resistivity rapidly. Therefore when \( N < N^* \) the resistivity will decrease slowly as \( N \) increases and when \( N > N^* \) the resistivity will decrease quickly.
CHAPTER IV

THE EFFECT OF TEMPERATURE

Chapter 2 introduced the physics of the bistable cell and Chapter 3 reviewed the modified trapping model. This chapter will first analyze the polysilicon resistor with respect to temperature and then will apply this analysis to the cell to discover the limiting constraints placed on the cell by temperature. These constraints together with the four governing equations will specify the resistor.

A. THE EFFECT OF TEMPERATURE ON THE RESISTOR

First reconsider (29), the transport equation. The following terms $p(0)$, $(kt/2\pi m_k^*)^{1/2}$, and $\exp(-qV_B/kT)$ increase as temperature increases. These terms overwhelm the sinh factor and produce a negative temperature coefficient of resistance (TCR).

At low doping concentrations, $N < N^*$. $|E_F|$ is small and $p(0)$ is highly dependent on temperature. As $N$ increases $E_F$ increases and $p(0)$ eventually becomes only a weak function of temperature. $V_B$ is temperature independent for $N < N^*$. However as $N$ increases above $N^*$, $V_B$ becomes a function of temperature, increasing at lower temperatures, and therefore contributes to a negative TCR. Since $V_B$ decreases rapidly as the doping concentration increases above $N^*$, it's significance is reduced and $p(0)$, whose sensitivity to temperature is decreasing, remains the dominate factor. So, as the doping concentration increases the temperature sensitivity of the resistor will decrease.

B. THE EFFECT OF TEMPERATURE ON THE BISTABLE CELL

Reconsider (21), the second governing equation. The limiting constraint occurs
when \( T_{\text{full}} \) is a minimum and \( T_{\text{empty}} \) a maximum. Since the bit line is capable of totally emptying the cell, and since the charge pump can maintain the empty state, \( Q_p \) in the empty state is always \( \sim 0 \). Therefore, in the empty state, \( \phi_{ss}(0) = \phi_{ss}(t_1) \) and (23) can be used to determine the time \( T_{\text{empty}} \). \( T_{\text{empty}} \) is inversely proportional to \( I \). So, over a temperature range of \( 0 - 100^\circ\text{C} \), \( T_{\text{empty}} \) will be a maximum at \( 0^\circ\text{C} \).

The analysis of the full state is only slightly more complicated because both (22) and (23) must be used to calculate \( T_{\text{full}} \). Eq. (22) should be used when \( V_g \leq V_g(t_1) \) and (23) when \( V_g \geq V_g(t_1) \). \( T_{\text{full}} \) will be the sum of the two times found. Because \( T_{\text{full}} \) is also inversely proportional to \( I \), \( T_{\text{full}}(\text{min}) \) occurs at \( 100^\circ\text{C} \).

\[
T_{\text{full}}(\text{min}) = T_{\text{full}}(100^\circ\text{C}) \quad \text{and} \quad T_{\text{empty}}(\text{max}) = T_{\text{empty}}(0^\circ\text{C}).
\]

Therefore to satisfy (21), \( T_{\text{full}}(100^\circ\text{C}) \) must be greater than \( T_{\text{empty}}(0^\circ\text{C}) \). If the resistance varies too much from \( 0 - 100^\circ\text{C} \), \( T_{\text{empty}}(0^\circ\text{C}) \) will exceed \( T_{\text{full}}(100^\circ\text{C}) \) and a suitable \( T_B \) will not exist. The resistance variation with temperature decreases as the doping concentration increases. So there is some minimum doping concentration that must be used to satisfy (21).

C. COMPUTER ANALYSIS

A computer program was written to determine the minimum doping concentration. The basic cell parameters used in the program were specified by Dr. Çilingiroğlu and are listed in Table I [6]. The main program, INT, integrates (22) and (23) as necessary to find \( T_{\text{full}} \) and \( T_{\text{empty}} \) for a Boron doped resistor. The values of \( E_A \), the impurity level of Boron, and \( E_g \), the band gap energy were calculated using formulas found in [7]. The main program and the subroutines selected the full state model or the empty state model by simply testing the temperature. Since the resistor was tested for a range of \( 0 - 100^\circ\text{C} \), the calculations were per-
formed for the full state when \( T > 50^\circ C \) and for the empty state when \( T < 50^\circ C \). Unless otherwise stated a state-of-the-art resistor was assumed, with characteristic dimensions \( 5\mu m \times 5\mu m \times .3\mu m [7] \). For \( L = 1220\AA, 420\AA, \) and \( 230\AA, N_g = 42, 117, \) and 218 grains respectively.

**TABLE I.**

**BISTABLE RAM CELL PARAMETERS. SPECIFIED BY ÇILINGIROĞLU [6].**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{rb} )</td>
<td>Refresh base voltage</td>
</tr>
<tr>
<td>( V_{rp} )</td>
<td>Refresh peak voltage</td>
</tr>
<tr>
<td>( t_{ox} )</td>
<td>Oxide thickness</td>
</tr>
<tr>
<td>( A_s )</td>
<td>Source gate area</td>
</tr>
<tr>
<td>( A_p )</td>
<td>Pump gate area</td>
</tr>
<tr>
<td>( N_D )</td>
<td>Substrate doping concen</td>
</tr>
<tr>
<td>( N_{st} )</td>
<td>Surface-state density</td>
</tr>
</tbody>
</table>

Subroutine F2 calculates \( V_{gz}, H, V_0^{1/2}, \) and \( \phi_{sp}(0)(\min) \) and \( V_g(t_1)(\min) \) for the full state. These variables are independent of the doping concentration but dependent on temperature. \( H \) is found by incrementing \( V_g \) from \( V_g(t_1) \) to \( V_{gz} \) and calculating \( \phi_{sp} \) at each point. A least squares algorithm is applied to find the slope, \( d\phi_{sp}/dV_g \), of the best fitting straight line. Since \( H \) is only approximately linear, the value of \( H \) in the full state will differ from the value of \( H \) in the empty state because \( V_g(t_1) \) is different for each state. Figure 11 is a flowchart of this subroutine.

Subroutines G1 and G2 derive \( p(0), V_B, \) and \( W \) for \( N > N^* \) and \( N < N^* \) respectively. Subroutine NST iteratively calculates \( N^* \) from (28). Figures 12 and 13 are flowcharts of G1 and G2. A flowchart of NST has not been included because of the simplicity of the subroutine.

The main program begins by calculating \( T_{empty} \) at \( T = 0^\circ C \) with NST,F2 and then either G1 or G2 depending on the doping concentration. After these calculations are completed all the parameters needed to find \( J_B \) in (29) will be
Fig. 11 Subroutine F2 flowchart. The numbers in parenthesis refer to equations in this document.
known for a given $V_g$. Here the program calls QA05A/AD, a numeric integration system subroutine, which is capable of integrating a function. QA05A/AD requires that the user define a function which will return a derivative, in this case $dt/dV_g$, when it receives the independent variable, $V_g$, from the calling routine. The value of $t$ returned by QA05A/AD is $T_{empty}$. The temperature is then changed to 100°C.
and the above procedure is repeated resulting in $T_{full}$. Figure 14 is a flowchart of the main program.

The user defined function DER, which is called by QA05A/AD, is flowcharted in Figure 15 and considers the effect of bulk crystallite resistivity.

The main program is structured so that a number of different parameters can be varied. Appendix A contains a listing of the main program and each of the subroutines with the exception of QA05A/AD and the least squares algorithm.
START

HOLE MOBILITY (35)

CRYSTALLITE RESISTIVITY (34)

INITIALIZE VARIABLES
V_{gr} = (V_{grain} - V_g) / N_g
V_{ba} = V_{grain}, V_c = 0
J_B = 1, J_c = 0

NO

J_c ≤ J_B?

YES

J_B (29)
J_c (36)

V_c = V_c + 0.01
V_{ba} = V_{grain} - V_c

\frac{dV_g}{dt} = J_B / H

\frac{d\text{ER}}{dt} = \frac{dV_g}{dV_g}

RETURN ER

THE VALUE OF H IS DEPENDENT ON THE STATE OF THE CELL AND V_g

Fig. 14 Flowchart of Main program, INT.
START

HOLE MOBILITY (35)

CRYSTALLITE RESISTIVITY (34)

INITIALIZE VARIABLES

\[ V_{\text{grain}} = \frac{(V_{r.p} - V_g)}{N_g} \]

\[ V_{ba} = V_{\text{grain}}, \; V_c = 0 \]

\[ J_B = 1, \; J_C = 0 \]

NO

\[ J_C \leq J_B? \]

YES

\[ J_B (29), \; J_C (36) \]

\[ V_c = V_c + 0.001 \]

\[ V_{ba} = V_{\text{grain}} - V_c \]

\[ dV_g/dt = J_B / H \]

\[ \text{DER} = dt / dV_g \]

RETURN DER

THE VALUE OF H IS DEPENDENT ON THE STATE OF THE CELL AND V_g

Fig. 15 Flowchart of user defined function, DER.
D. THE VARIATION OF $T_{B_{safety}}$ WITH DOPING CONCENTRATION

$T_{B_{safety}}$ is defined as the difference $T_{full} - T_{empty}$ and must be positive if (21) is to have a solution. Figure 16 is a graph of the output from a variation of INT which logarithmically increments the resistor doping concentration and records $T_{B_{safety}}$ at each point. Notice that, as predicted, the initially negative $T_{B_{safety}}$ steadily increases toward zero and then changes sign indicating that $T_{full} > T_{empty}$ and (21) has a solution. Note however that for $N \geq 10^{17.9}$ $T_{B_{safety}}$ begins to decrease slowly. The reason is that at such high doping concentrations the depletion region width is narrow and the bulk crystallite resistivity begins to contribute significantly to the total resistivity of the material. Since the effect of temperature on the mobility was neglected, the crystallite has a slightly negative TCR and thus $T_{B_{safety}}$ decreases slightly.

Figure 17 simply reiterates the concept just presented in a slightly different manner. Here INT has been adjusted so that $T_{B_{safety}}$ is calculated for successively larger temperature operating ranges. As the operating range is increased the sensitivity of the resistor to temperature causes the refresh mechanism to fail and $T_{B_{safety}}$ goes negative.

E. THE VARIATION OF THE MINIMUM ALLOWABLE DOPING CONCENTRATION WITH GRAIN SIZE

Table II lists $N^*$ and the lowest value of $N$ for which $T_{B_{safety}}$ is positive for $L = 1220\,\text{Å}, 420\,\text{Å},$ and $230\,\text{Å}$. As the grain size decreases the disorder of the material increases and $Q_1$ increases. This pushes $N^*$ up, preserving the high resistivity and TCR at higher doping concentrations. Therefore the resistivity and the TCR will begin their rapid decent at progressively higher doping concentrations as the grain...
size decreases. So as the grain size decreases, a higher doping concentration will be necessary to achieve the same insensitivity to temperature.

F. THE VARIATION OF $T B_{\text{safety}}$ WITH THE NUMBER OF GRAINS

Table III lists the value of $T B_{\text{safety}}$ at two doping concentrations for $L = 1220\text{Å}$ and $N_g = 42, 52, 62, 72$ and $82$ grains. In Table III $|T B_{\text{safety}}|$ increases as $N_g$ increases. This can be explained as follows.
Fig. 17 $T_{B_{\text{safe}}}$ versus temperature range.
TABLE II.
THE MINIMUM ALLOWABLE DOPING CONCENTRATIONS
FOR THREE GRAIN SIZES

<table>
<thead>
<tr>
<th>~N* (cm⁻³)</th>
<th>N (cm⁻³)</th>
<th>L (Å)</th>
<th>Qt (cm⁻²)</th>
<th>N_g</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 × 10¹⁷</td>
<td>10¹⁷.⁸</td>
<td>1220</td>
<td>1.90 × 10¹²</td>
<td>42</td>
</tr>
<tr>
<td>6.7 × 10¹⁷</td>
<td>10¹⁸.²</td>
<td>420</td>
<td>3.00 × 10¹²</td>
<td>119</td>
</tr>
<tr>
<td>1.4 × 10¹⁸</td>
<td>10¹⁸.⁴</td>
<td>230</td>
<td>3.34 × 10¹²</td>
<td>217</td>
</tr>
</tbody>
</table>

TABLE III.
TB_{safety} FOR TWO DOPING CONCENTRATIONS
AND SEVERAL VALUES OF N_G

<table>
<thead>
<tr>
<th>TB_{safety} (sec)</th>
<th>N_g</th>
<th>N (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6.7233 × 10⁻¹¹</td>
<td>42</td>
<td>10¹⁷.⁷</td>
</tr>
<tr>
<td>-9.5220 × 10⁻¹¹</td>
<td>52</td>
<td>10¹⁷.⁷</td>
</tr>
<tr>
<td>-1.2866 × 10⁻¹⁰</td>
<td>62</td>
<td>10¹⁷.⁷</td>
</tr>
<tr>
<td>-1.5982 × 10⁻¹⁰</td>
<td>72</td>
<td>10¹⁷.⁷</td>
</tr>
<tr>
<td>-1.9733 × 10⁻¹⁰</td>
<td>82</td>
<td>10¹⁷.⁷</td>
</tr>
<tr>
<td>+4.1030 × 10⁻¹¹</td>
<td>42</td>
<td>10¹⁷.⁸</td>
</tr>
<tr>
<td>+5.0175 × 10⁻¹¹</td>
<td>52</td>
<td>10¹⁷.⁸</td>
</tr>
<tr>
<td>+6.0363 × 10⁻¹¹</td>
<td>62</td>
<td>10¹⁷.⁸</td>
</tr>
<tr>
<td>+6.9206 × 10⁻¹¹</td>
<td>72</td>
<td>10¹⁷.⁸</td>
</tr>
<tr>
<td>+7.7913 × 10⁻¹¹</td>
<td>82</td>
<td>10¹⁷.⁸</td>
</tr>
</tbody>
</table>

The current through the resistor is given by

\[ I = I_s \sinh \left( \frac{qV_{ba}}{2kT} \right) \]  \hspace{1cm} (37)

where \( I_s \) is the pre-sinh factor in (29) multiplied by the cross-sectional area \( A \). \( I_s \) is independent of \( N_g \). Letting \( V_{ba} = (V_{rp} - V_g)/N_g - V_c \) and approximating the sinh by an exponential yields

\[ I = I_s \exp \left( \frac{-qV_c}{2kT} \right) \exp \left( \frac{-qV_{rp}}{2kTN_g} \right) \exp \left( \frac{-qV_g}{2kTN_g} \right). \]  \hspace{1cm} (38)

Substituting (38) in (22) or (23) yields

\[ I = I_s \exp \left( \frac{-qV_c}{2kT} \right) \exp \left( \frac{qV_{rp}}{2kTN_g} \right) \exp \left( \frac{-qV_g}{2kTN_g} \right) = A_p C_{ex} (1 - H^*) \frac{dV_g}{dt} \]  \hspace{1cm} (39)
where $H^*$ is the appropriate expression for $d\phi_{sp}/dV_g$. Solving (39) yields

$$\Delta t = \frac{2kTN_gA_pC_{oz}(1 - H^*)}{I_s q} \exp\left(\frac{-qV_c}{2kT}\right) \exp\left(-\frac{-qV_a}{2kTN_g}\right).$$ \hspace{1cm} (40)

Thus

$$TB_{safety} = N_g\left[K_1 \exp\left(\frac{qV_c}{2kT_1}\right) \exp\left(-\frac{-qV_a}{2kN_gT_1}\right) - K_2 \exp\left(\frac{-qV_c}{2kT_2}\right) \exp\left(-\frac{-qV_a}{2kN_gT_2}\right)\right]$$ \hspace{1cm} (41)

where $K_1$ is

$$K_1 = \frac{2kT_1A_pC_{oz}(1 - H^*)}{I_s q}$$ \hspace{1cm} (42)

for $T_1 = 373^\circ K$ and $T_2 = 273^\circ K$ and $I = 1, 2$ respectively.

For certain low doping concentrations where $V_c \ll V_a/N_g$, the exponential terms containing $V_c$ do not contribute to the value of $TB_{safety}$ and $|TB_{safety}|$ increases with $N_g$. As $N$ increases the width of the depletion region decreases and $V_c$ increases. Recall that $J_B = J_c$. So, from (29) and (36)

$$J_c \sinh\left(\frac{qV_{ba}}{2kT}\right) = V_c(L - 2W)\rho_c.$$ \hspace{1cm} (43)

Since $V_{ba} + V_c = V_a/N_g$, as $N_g$ increases $V_c$ and $V_{ba}$ will decrease. Eq. (43) reveals that $V_c$ will decrease more than $V_{ba}$. This will cause the difference between the two exponential terms containing $V_c$ to decrease and thus the sign of $TB_{safety}$ may change as $N_g$ is increased. Finally as $N$ increases still further so that $V_c \sim V_a/N_g$, the exponential terms in (41) cancel and $TB_{safety} \sim N_g(K_1 - K_2)$.

G. THE EFFECT OF TEMPERATURE ON $T_B$

In Chapter 2, four governing equations were presented. Three of these have been used to analyze the performance of the resistor. The remaining equation, (20),
states that \( I_p \geq I_L \). Assuming that \( J_L \), the worst case leakage current density is 
\( \sim 2 \text{amp/cm}^2 \), \( I_L = 2(A_p + A_s) \). If \( \alpha \) is small \( I_p \) can be found from (3) to be

\[
I_p = qA_sfN_{st}
\]

where \( f = 1/(T_B + T_P) \). \( T_P \) must be long enough to guarantee that \( V_p \) falls to \( V_{rp} \) in both states. If \( T_P = 5T_B \), [6] shows that

\[
I_p = \frac{qA_fN_{st}}{6T_B}.
\]

Values for \( A_p \), \( A_s \), and \( N_{st} \) are given in Table I. Substituting these in (45) yields

\[
222.2 \times 10^{-6} \text{sec} \geq T_B.
\]

The values of \( T_B \) found at six different doping concentrations are given in Table IV where

\[
T_B = \frac{T_{\text{full}} + T_{\text{empty}}}{2}.
\]

\( T_B \) is in every case smaller than the constraining time of \( 222.2 \times 10^{-6} \text{(sec)} \). However \( T_B \) is so small that \( \alpha \) in (3) may be significant. This means that during a full state at temperatures near 100°C some of the stored charge may be pumped into the substrate because the inversion layer is being removed too quickly.

### Table IV.

**THE VARIATION OF \( T_B \) WITH DOPING CONCENTRATION.**

\( \text{NG} = 42 \) AND \( L = 1220 \text{Å} \).

<table>
<thead>
<tr>
<th>( T_{\text{B}_{\text{safty}}} ) ( (\text{sec}) )</th>
<th>( N ) ( (\text{cm}^{-3}) )</th>
<th>( T_B ) ( (\text{sec}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( -6.3528 \times 10^{-09} )</td>
<td>( 10^{17.5} )</td>
<td>( 4.0850 \times 10^{-7} )</td>
</tr>
<tr>
<td>( -9.6253 \times 10^{-10} )</td>
<td>( 10^{17.8} )</td>
<td>( 9.5794 \times 10^{-8} )</td>
</tr>
<tr>
<td>( -6.7233 \times 10^{-11} )</td>
<td>( 10^{17.7} )</td>
<td>( 2.8069 \times 10^{-8} )</td>
</tr>
<tr>
<td>( +4.1030 \times 10^{-11} )</td>
<td>( 10^{17.8} )</td>
<td>( 1.2280 \times 10^{-8} )</td>
</tr>
<tr>
<td>( +4.8316 \times 10^{-11} )</td>
<td>( 10^{17.9} )</td>
<td>( 7.4580 \times 10^{-9} )</td>
</tr>
<tr>
<td>( +4.4879 \times 10^{-11} )</td>
<td>( 10^{18.0} )</td>
<td>( 5.4757 \times 10^{-9} )</td>
</tr>
</tbody>
</table>
CHAPTER V

CONCLUSIONS

A. ACCURACY OF THE CALCULATIONS

The computer analysis performed has four major sources of error. The modified trapping model introduces a small amount of error at low temperatures, > 25°C, because it does not include thermionic field emission. Lu's model may also produce significant error at or around $N^*$ because the grains of the resistor are not all the same size and will not all reach a fully saturated condition at the same doping concentration [7].

The second source of error is the numerical integration routine, QA05A/AD. This standard routine performs its own checks for accuracy and alerts the user to potentially faulty calculations. Since the program executed without these warnings, the results were accepted as valid.

The calculation of $\mu_h$, the hole mobility, assumes $\mu_h$ is temperature independent. This will introduce significant error at low ($< N^*$), doping concentrations, but not at higher concentrations because the mobility becomes less sensitive to temperature at high doping concentrations. Since the interesting range of doping concentrations, those that produced a positive $TB_{safety}$, was $> N^*$, the error introduced will be small.

B. SUGGESTIONS FOR FURTHER WORK

The sensitivity of the resistor to temperature is a major disadvantage of the cell. However it appears that only the resistor, and not the other devices in the cell,
is the major cause of the problem. The following two suggestions for further work are made with this in mind.

First an attempt should be made to optimize the cell with respect to area and temperature operating range. An optimization procedure is given below. Second an alternative to the resistor should be found and tested in the cell. Currently, at Texas A&M University, Dr. Çilingiroğlu is exploring alternatives to the resistor.

The optimization of the cell with respect to area and temperature mentioned above should proceed in the following manner. First a state-of-the-art resistor and pump gate area should be assumed. Second $T_E$ should be equated to 1µs, which is approximately the smallest acceptable value for which $\alpha$ in (3) can be neglected. Then the storage gate should be specified so that it is large enough to accommodate the sensing mechanism when $V_g = V_{rp}$. The refresh voltage should then be decreased until the temperature range is acceptable. (Note that if the refresh voltage is decreased the storage gate area may need to be increased because of the sensing mechanism.) Should these specifications fail to produce a working cell the area of the pump gate may be increased. The storage well should then be readjusted to meet the previous constraint.
REFERENCES


SUPPLEMENTAL SOURCES CONSULTED


MAIN PROGRAM
NUMERICAL INTEGRATION PROGRAM
IMPLICIT REAL*8(A-Z)
INTEGER+4 IFLAG, LEVEL
EXTERNAL DER
COMMON T,VOX,PHISMIN,VG1FULL,SLOPE,NI,EG,
N,P0,OT,W,ET,LNSTAR,VB,EA,PI,KS,KSIO2,
E0,ES,Q,K,H,EMASS,WH,ME,TOX,QSS,ND,
VRP,VRB,AS,AP,COX,UE,SVO,NG,EF

CONSTANTS
pi = 3.1415927
Ks = 11.6
Ksio2 = 3.9
e0 = 8.854*(10.**-14.)
e = 11.8 * e0
q = 1.6*(10.**-19.)
k = 1.38*(10.**-23)
h = 6.625 * 10.**-34.0
e mass = 9.1 * 10.**-31.0
mh = 0.38*emass
me = 0.28*emass

SPECIFIED CELL PARAMETERS
Tox = 750.*10.**-8.0
Qss = 5.0 *10.**10.0
Nd = 5.0*10.**14.0
Vrp = -10.0
Vrb = 0.0
As = 120.0*10.**-8.0
Ap = 24.0*10.**-3.0
Cox = e0*Ksio2/Tox
ET = -.17

NUMERICAL INTEGRATION PARAMETERS
AERR = 10.0**-22.0
RERR = .001
LEVEL = 1

INTERACTIVE INPUTS
CALL LIB$ERASE_PAGE(1,1)
CALL LIB$SET_CURSOR(16,1)
TYPE '( 'ENTER L' ' )'
ACCEPT = 'L'
TYPE 'L'

IF (L.EQ.1228) THEN
  QT = 1.9*10.**12.
  NG = 42
OPEN (UNIT=6,FILE='[JBROWN.THESIS.NOW]DATA122. ',STATUS='NEW')
OPEN (UNIT=10,FILE='[JBROWN.THESIS.NOW]T122. ',STATUS='NEW')
ELSE IF (L.EQ.420) THEN
  QT = 3.10.**12.
  NG = 119
OPEN (UNIT=6,FILE='[JBROWN.THESIS.NOW]DATA420. ',STATUS='NEW')
OPEN (UNIT=10,FILE='[JBROWN.THESIS.NOW]T1220. ',STATUS='NEW')
ELSE IF (L.EQ.230) THEN
QT = 3.34*10.**12.
NG = 217
OPEN (UNIT=6,FILE='[JBROWN.THESIS.NOW]DATA230.',STATUS='NEW')
OPEN (UNIT=10,FILE='[JBROWN.THESIS.NOW]DATA230.',STATUS='NEW')
ELSE
  TYPE *, 'ERROR NO L MATCH'
END IF
WRITE (10, '(E13.5)'), L
WRITE (6, '(E13.5)'), L
TYPE '('' ENTER INCSTART '').' ACCEPT *, INCSTART
TYPE '('' ENTER INCMAX '').' ACCEPT *, INCMAX

L = L=10.*-8. NSTART = 10.* INCSTART NMAX = 10.* INCMAX N = NSTART INC = INCSTART

C
DO LOOP TO INCREMENT THE DOPING CONCENTRATION
DO WHILE (N.LT.NMAX)
  TYPE *, N
  C
  CALCULATE TEMPTY AT 273 DEGREES C
  T = 273
  Eq = 1.16 - (7.02*10.0**-4.0)*(T**2.0)/(T + 1108.0)
  EA = -EG/2. + 0.08-4.3*10.**-8. *(N**((1./3.))
  uh = 47.7*(495.8-47.7)/(1.8+(N/(6.3*10.8*16.0)))**.76)
  LNI = 124.38048 + 1.5*DLOG(2*PI*K*T-Q*EG/(2.*K*T)
  NI = EXP(LNI) * (1./100.)**3.
  CALL NST
  CALL F2
  IF (N.GT.NSTAR) THEN
    CALL G1
  ELSE
    CALL G2
  END IF
  CALL QA5AD(TIME, DER, VRP, VGX, AERR, RERR, LEVEL, ERROR, IFLAG)
  IF (LEVEL.GE.4) THEN
    TYPE *, 'LEVEL = ', LEVEL
  END IF
  TEMPTY = TIME
  C
  CALCULATE TFULL AT 373 DEGREES C
  T = 373
  Eq = 1.16 - (7.02*10.0**-4.0)*(T**2.0)/(T + 1108.0)
  EA = -EG/2. + 0.08-4.3*10.**-8. *(N**((1./3.))
  uh = 47.7*(495.8-47.7)/(1.8+(N/(6.3*10.8*16.0)))**.76)
  LNI = 124.38048 + 1.5*DLOG(2*PI*K*T-Q*EG/(2.*K*T)
  NI = EXP(LNI) * (1./100.)**3.
  CALL NST
CALL F2
IF (N .GT. NSTAR) THEN
   CALL G1
ELSE
   CALL G2
END IF
CALL QA05AD(TIME, DER, VRP, VGX, AERR, RERR, LEVEL, ERROR, IFLAG)

IF (LEVEL .GE. 4) THEN
   TYPE *, 'LEVEL = ', LEVEL
END IF

TFULL = TIME
TBSAFETY = TFULL - TEMPTY
AVE = (TFULL + TEMPTY)/2.
TB = AVE/(1.5*10.**3)
WRITE (10, '(4E13.3)'), TBSAFETY, AVE, N, TB

INC = INC + .1
N = 10.**INC
END DO
CLOSE(6)
CLOSE(18)
END

FUNCTION DER(VG)
IMPLICIT REAL*8(A-Z)
COMMON T, VGX, PHISMIN, VG1FULL, SLOPE, N1, EG,
   C N, PO, QT, W, ET, L, NSTAR, VB, EA, PI, KS, KS02,
   C E9, ES, Q, K, H, Dmass, MH, ME, TOX, QSS, ND,
   C VRP, VRB, AS, AP, COX, UH, SVO, NG, EF

pc = 1.8/(uh*po*q)
Vgrain = (Vrb - Vg)/Ng
Vbo = Vgrain
Vc = 0.6

JB = 1.0
JC = 0.0

C ITERATIVE CALCULATION OF JB
Do While (JC .lt. JB)
   R = (k*T/(2.0*pi*mh))**.5
   st = (exp(q*Vbo/(2.0*k*T)) - exp(-q*Vbo/(2.0*k*T)))/2.0
   JB = 2.0*q*po*R*exp(-q*Vb/(k*T)) + st*100.0
   Vc = Vc + .0001

   IF (VC .GT. VGRAIN) THEN
      VC = VGRAIN
   END IF

   Vbo = Vgrain - Vc

   ARG = L - W*2.

   JC = 0 IF THE GRAIN IS COMPLETELY DEPLETED
   IF (ARG .EQ. 0) THEN
      goto 7
   ELSE
      ...
JC = Vc/((L-2.0+W)*pc)
END IF
end do
CONTINUE
IF (JB . EQ. 0.0) THEN
  JB = Vgroin/((L-2.0+W)*pc)
  TYPE = 'JB = 0', 'DER'
END IF

USE THE APPROPRIATE VALUE OF H DEPENDING ON THE STATE OF THE CELL
IF (T. EQ. 273) THEN
  DDER = JB/((Ap+Cox)*(1.0-slope))
ELSE IF (VG. LT. VG1FULL) THEN
  bot = 1.0-Ap/((Ap+As)*(1.0+Svo/(2.0*(-PHISMIN)**0.5)))
  DDER = JB/(Ap+Cox*bot)
ELSE
  DDER = JB/((Ap+Cox)*(1.0-slope))
END IF
DER = 1.0/DDER
RETURN
END
SUBROUTINE Gl
C CALCULATE PO, VB, AND W FOR N>NSR
IMPLICIT REAL(A-Z)
COMMON T, VGX, PHISMIN, VG1FULL, SLOPE, NI, EG
COMMON N, PO, QT, W, ET, L, NSTAR, VB, EA, PI, KS, KS102
COMMON EB, ES, Q, K, H, EMASS, ME, TOX, QSS, ND
COMMON VRP, VRB, AS, AP, COX, UH, SVO, NG, EF
C CALCULATE THE FERMI LEVEL
C INITIALIZE THE DO LOOP PARAMETERS
EF = 0.0
ACCURACY = 1.0
DO WHILE (ACCURACY. GT. .01)
   EF = EF - .00001
   PO = (NI)*EXP(-((EF*Q)/(K*T)))
   NPLUS = (N)/(1+2*EXP((EA-EF)*Q/(K*T)))
   SMALLEST = DMIN1(PO, NPLUS)
   DIF = ABS(PO-NPLUS)
   ACCURACY = DIF/SMALLEST
   IF (EF .LT. -.56) THEN
      TYPE *, 'ACCURACY ON EF UNACHIEVABLE'
   END IF
END IF
END DO
C CALCULATE THE WIDTH OF THE DEPLETION REGION
C INITIALIZE THE DO LOOP PARAMETERS
W = L/2.
INC = W*.001
RIGHT = W - 1
DO WHILE (W .GT. RIGHT)
   W = W - INC
   ARG = Q*Q*N+W*W/(2*ES*K*T)
   IF (ARG .LT. 50) THEN
      RIGHT = QT/((2*N)*(1+2*(NI/NPLUS)*)EXP(-ET*Q/(K*T))
   C EXP(Q*Q*N+W*W/(2*ES*K*T)))
   END IF
END DO
C CHECK ACCURACY
SMALLEST = DMIN1(W, RIGHT)
DIF = ABS(W - RIGHT)
ACCURACY = DIF/SMALLEST
IF (ACCURACY. GT. .01) THEN
   TYPE *, 'DESIRE ACCURACY NOT OBTAINED, W'. W
END IF
C CALCULATE VB
VB = Q*Q*N+W*W/(2.*ES)
WRITE (6, '(1X, ' 'THIS IS Gl')')
WRITE (6, '(1X, ' 'T = ' '.E13.5')') T
WRITE (6, '(1X, ' 'PO ' ', 13X, ' 'NPLUS' ', .6X, ' 'VB' ', 13X, ' 'EF' ')')
WRITE (6, '(1X, ' 'EA ' ', 13X, ' 'EG' ', 13X, ' 'W' ')')
WRITE (6, '(1X, ' 'NI ' ', 13X, ' 'EA ' ', 13X, ' 'W' ')')
RETURN
END
SUBROUTINE G2
CALCULATE PO, VB, AND W FOR N=STAR
IMPLICIT REAL*8(A-Z)
COMMON T,VGX,PHISMIN,VG1FULL,SLOPE,NI,EG,
N,PO,QT,W,ET,L,NDSTAR,VB,EA,PI,KS,KS102,
E0,ES,Q,K,H,EMASS,WH,ME,TOX,OSS,ND,
VRP,VRB,AS,AP,COX,UM,SVO,NG,EF

GRAIN IS COMPLETELY DEPLETED
W = L/2.0

CALCULATE THE POTENTIAL BARRIER HEIGHT
VB = q*W*W/(2.*es)

CALCULATE EF
EF = et - VB + k*T/q + DLOG(.5*(Q/((L+N) - 1.0))

CALCULATE P(0)
p0 = n*i*exp(-EF*q/(k*T))
WRITE (6,'(1X,'"This is G2"')')
WRITE (6,'(1X,"T = "',E13.5')',T
WRITE (6,'(1X,"PO = "',13X,"NPLUS",6X,"VB")').PO,PO,VB
WRITE (6,'(1X,"NI = "',13X,"EA",6X,"EG")').NI,EA,EG
WRITE (6,'(1X,3E13.5')').NI,EA,EG
RETURN
END
SUBROUTINE NST
IMPLICIT REAL*8(A-Z)
COMMON T, VGX, PHISMIN, VG1FULL, SLOPE, NI, EG,
   N, PO, QT, W, ET, L, NSTAR, VB, EA, PI, KS, KS102,
   E0, ES, Q, K, H, EMASS, MH, ME, TOX, QSS, NO,
   VRP, VRB, AS, AP, COX, UH, SVO, NC, EF

LEFT  = 0.0
RIGHT = 1.0
NSTAR = 10.**17.
INC   = 10.**14.

DO WHILE (LEFT.LT.RIGHT)
   NSTAR = NSTAR + INC
   LEFT  = Q*Q*NSTAR+L*L/(8*ES*K*T)-ET*Q/(K*T)
   RATIO = QT/(L*NSTAR)
   IF (RATIO.LE.1) THEN
      NSTAR = QT/L
      TYPE = 'RATIO LT 1'
   ELSE
      RIGHT = DLOG(QT/L - NSTAR)-DLOG(2.*NI)
   END IF
END DO

SMALLEST = DMIN1(LEFT,RIGHT)
DIF = ABS(LEFT-RIGHT)
ACCURACY = DIF/SMALLEST

IF (ACCURACY.LT.0.01) THEN
   TYPE = 'DESIRED ACCURACY NOT OBTAINED, NSTAR',NSTAR
END IF

RETURN
END
SUBROUTINE F2
IMPLICIT REAL*8(A-Z)
DIMENSION VG(500),PHISP(500),RESIDVEC(500)
INTEGER M
COMMON T,VGX,PHISMIN,VG1FULL,SLOPE,NI,EG,
C C VRP,VRB,AS,AP,COX,UH,SVO,NG,EF

* THE BODY FACTOR
  sVo = (2.0*e0*Ks*q*Nd)**.5 + 1.0/Cox
  Vo = sVo**2.0

* THE SURFACE POTENTIAL FOR WHICH n = p = ni (n,p ARE SURFACE DENSITIES)
  phiT = -k*T/q*(DLOG(Nd/ni))

* THE WORK FUNCTION DIFFERENCE ASSUMING THE GATE IS DOPED INTO THE
  CONDUCTION BAND
  phims = - Eg/2.0 - phiT

* THE FLAT-BAND VOLTAGE
  Vfb = phims - (Qss=q)/Cox

* GATE VOLTAGE FOR WHICH PHISP = PHIF
  Vgx = Vfb + phiT - sVo + (-phiT)**.5

* FIND THE MINIMUM STORAGE SURFACE POTENTIAL AT T = 0
  Qtmax = As + Cox * (-Vrp + Vfb + 2.0*phiT - sVo + (-phiT)**.5)
  c = Qtmax/(Cox*(Ap + As)) + Vrp - Vfb
  b = sVo
  a = 1.0
  x = (-b + (b**2.0 - 4*a*c)**.5)/(2.0*a)
  phismax = -(x**2.0)
  Qtmin = As + Cox * (-Vrp + Vfb + phismax - sVo + (-phismax)**.5)
  c = Qtmin/(Cox*(Ap + As)) + Vrp - Vfb
  b = sVo
  a = 1.0
  x = (-b + (b**2.0 - 4*a*c)**.5)/(2.0*a)
  phismin = -(x**2.0)

* CALCULATE VG AT T = T1 FOR THE FULL STATE
  Vglfull = Vfb + phismin - sVo + (-phismin)**.5

* CALCULATE THE SLOPE
  M = 500
  If (T .LT. 323.) then
    vg(1) = -10.0
  else
    vg(1) = Vglfull
  end if

  Do j = 1,M
    phisp(j) = (-.5*(-sVo + (Va - 4.0*(vg(j) - Vfb)**.5))**2.
    vg(j+1) = vg(j) + (-vg(1) + Vgx)/M
  end do
LEAST SQUARES APPROXIMATION (COURTESY DR. FLEMING)
CALL LSQLINE (M,Vg,phi,slope,intercept,residvec,sumsq,ierr)
RETURN
END
APPENDIX B

LETTER OF PERMISSION
Ms. Jenny Brown  
P. O. Box 13660  
College Station, TX 77841  

Dear Ms. Brown:

As per your request, this letter is used to give my permission for you to use figures and data which I published in my Ph.D. dissertation entitled "Monolithic Polycrystalline-Silicon Passive Devices: Theory, Realization, and Applications," Technical Report No. G549-1, Stanford University, Stanford, CA.

Best Wishes for your M.S. Thesis.

Sincerely,

Nicky Lu
VITA

Janet Kay Brown received her B.S. in Electrical Engineering in December 1983 from Texas A&M University. Her M.S. from Texas A&M University is expected in May 1986. Her permanent mailing address is

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