Blowing of polycrystalline silicon fuses

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Polycrystalline silicon fuses are one time programmable memory elements which allow the calibration of integrated circuits at wafer and package level. We present a zero-dimensional lumped parameter model of the programming of fuses made from a combination of tungsten silicide and polycrystalline silicon. The components of the model are an electrical model, a thermal model, and a flow model. The model generates quantitatively accurate results and reproduces trends with applied voltage and fuse size. © *2010 American Institute of Physics*. [doi:10.1063/1.3457469]

Polycrystalline silicon fuses are one time programmable memory elements in silicon chips. They are utilized as permanent on chip memory storage for calibration factors in precision analog circuits and can be programmed (blown) at both wafer and package levels. Polycrystalline silicon fuses are constructed from layers of polycrystalline silicon and metal silicides. Theories of the blowing process which have been put forward invoke grain recrystallization,[1] melting and vaporization,[2] and electromigration.[3]

One fuse design is shown in Fig. 1. The fuse is completely solid state and consists of layers of conducting tungsten silicide and semiconducting polycrystalline silicon surrounded by insulating silica. The thickness of the polycrystalline silicon and tungsten silicide layers are a_1 and a_2, respectively, the width of the fuse is b and its length is c. The electrodes on either side of the fuse are made from the same materials with the same thickness but are much larger in the other two directions.

The fuse is blown by the application of a fixed potential bias across the fuse. Current versus time graphs are shown for different voltages and different size fuses in Fig. 2. The microstructure of a blown $0.3 \times 0.3 \times 1.5$ μm^3 fuse is shown in Fig. 3. The following features of the blowing process are apparent: (i) there is evidence of melting of the fuse, and of parts of the electrodes and the silica surrounding the fuse and (ii) the fuse is disconnected by both a void and by a layer of silica. A model of the fuse blowing process must explain these observations.

We propose that the fuse blowing process occurs by the following steps. (1) When the current starts to flow, it flows mostly through the metallic silicide. As the fuse heats up, the silicide conductivity reduces but the conductivity of the semiconducting polycrystalline silicon increases until it is the dominant conductor. The overall effect is that the conductivity of the fuse first increases then decreases. (2) Eventually the fuse, parts of the electrodes and some of the silica surrounding the fuse melt. (3) Electromigration drives the fuse material toward the cathode. This displaces the insulating molten silica toward the anode, where it begins to pinch off the fuse from the anode. (4) When pinch off is nearly complete the fuse ruptures forming the void (this process is driven by the contraction of silicon on melting).

To model the fuse blowing process we use a lumped parameter approach. This model builds on work reported in Ref. 4. The lumped parameter model of the fuse consists of ordinary differential equations for the temperature, T, of the fuse, and the height, h, and width, w, of the pinched off region. These variables are illustrated in Fig. 4. An electronic model describes the temperature and geometry dependent resistance of the fuse; a thermodynamic model describes the heating and melting of the fuse and its surroundings; a flow model describes the electromigration driven pinch off of the fuse. The rupture of the fuse is not modeled explicitly; it is assumed that rupture occurs just as pinch off is complete.

(a) *Electronics.* Electrically the system consists of the fuse in series with a transistor. The fuse blowing process is initiated by a decrease in the transistor resistance from a very large value to R_t. This decrease occurs on a nanosecond timescale and is assumed to be instantaneous in the model. The fuse can be modeled as two resistors in series, with a total resistance R_f. The first resistor represents the part of the fuse unaffected by flow and has a temperature dependent resistance, R_1. The second resistor represents the region of the fuse in which pinch off occurs and thus has a temperature and geometry dependent resistance, R_2,

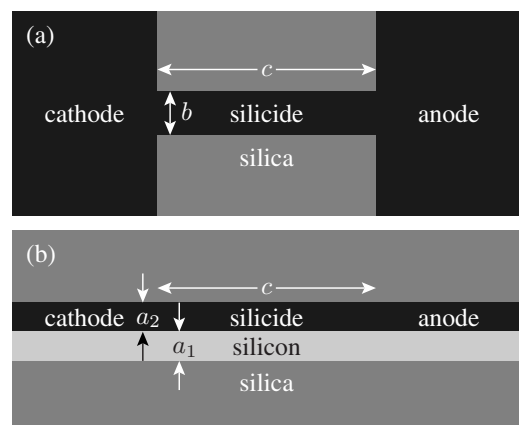$$R_1 = \frac{c}{\sigma(T)ab}, \tag{1}$$

FIG. 1. Polycrystalline silicon fuse geometry. (a) Top view. (b) Transverse cross-section.
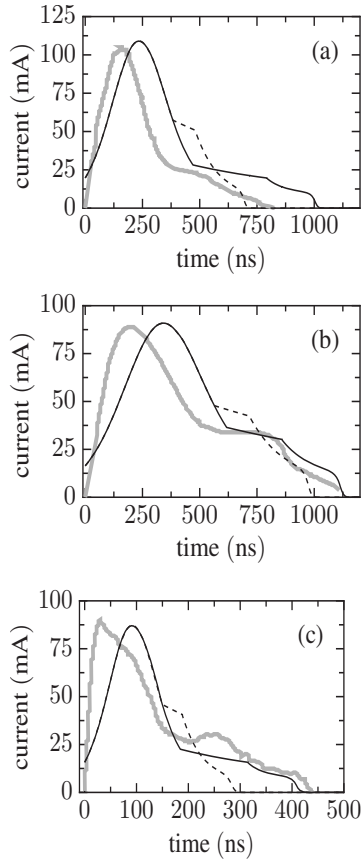
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FIG. 2. Current time curves for: (a) 6 V applied to a $0.3 \times 0.6 \times 3$ μm^3 fuse; (b) 5 V applied to a $0.3 \times 0.6 \times 3$ μm^3 fuse; (c) 4.8 V applied to a $0.3 \times 0.3 \times 1.5$ μm^3 fuse. Grey line: experiments. Solid and dotted black lines: simulations with and without superheating. Experimental curves in (a) and (b) were calculated from data in Ref. 2.

$$R_2 = \frac{h}{\sigma(T)a(b - 2w)}. \tag{2}$$

The current I flowing through the fuse is calculated from Ohm's law.

Following Ref. 5, conductivity, $\sigma(T)$, is taken to be a quadratic function of temperature. There is insufficient data to separate out the contributions of the polycrystalline silicon and tungsten silicide layers, therefore a single conductivity function is used for both layers of the fuse,
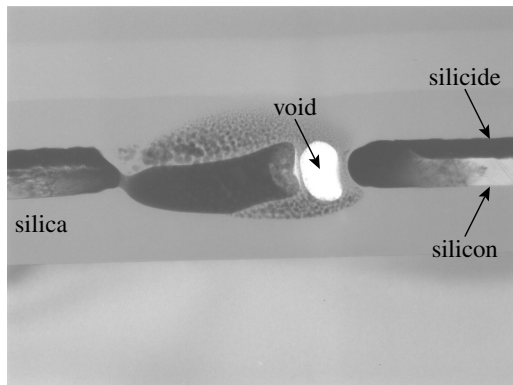

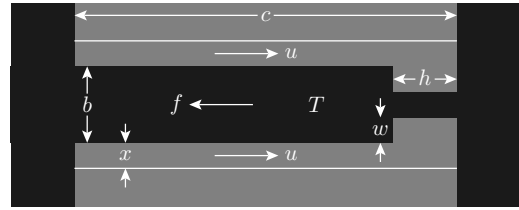FIG. 3. Electron micrograph showing the microstructure of a blown $0.3 \times 0.3 \times 1.5$ μm^3 fuse.

FIG. 4. Fuse variables: the temperature T of the fuse and the width, w, and height h of the pinched off region.

$$\sigma(T) = \sigma_0[1 - \alpha(T - T_{max})^2]. \tag{3}$$

As the fuse heats up, its conductivity increases until T_{max} is reached and then it decreases.

(b) *Thermodynamics.* The temperature, T, of the fuse is assumed to be homogeneous throughout the fuse. The equation modeling its evolution is

$$vC(T)\frac{dT}{dt} = I^2R_f - \frac{k_3s(T - T_0)}{d}. \tag{4}$$

The left hand side describes the heat capacity of the fuse. The terms on the right hand side describe Joule heating and Newtonian cooling, respectively. $C(T)$ is a the volume averaged heat capacity per unit volume of the fuse calculated from C_1 and C_2, the heat capacity per unit volume of polycrystalline silicon and tungsten silicide (assumed to be the same in the solid and liquid); and ΔH_1 and ΔH_2, the enthalpies of fusion per unit volume of polycrystalline silicon and tungsten silicide. In solving the equations, the melting phase transitions (at T_{m1} and T_{m2} in polycrystalline silicon and tungsten silicide, respectively) are assumed to have a finite width of δT. v is the volume of the fuse, k_3 is the thermal conductivity of silica, T_0 is room temperature and s is the surface area of the fuse, $2c(a_1 + a_2 + b)$, d is a thermal conduction length. A better fit to the data is obtained by allowing superheating of the tungsten silicide before it melts; this seems physically reasonable given the small size of the fuse and the rapid heating rates. In the model superheating is implemented by increasing the value of T_{m2} above its equilibrium value of 2300 K.

(c) *Fluid mechanics.* The body force driving electromigration is given by $f = g n_q I R_f/c$ where n_q is the charge density of charge carriers and g is a constant of proportionality. The force acts on the conducting silicon and silicide and is directed from the anode to the cathode. The viscosities of the molten silicon and silicide are much lower than that of molten silica. Therefore flow is limited by the motion of silica. The electromigration body force sets up a pressure gradient within the fuse which is transmitted to the molten silica surrounding the fuse and causes it to move with a velocity $u = fx^2/12\eta$ where η is the dynamic viscosity of molten silica and x is the width of the molten silica region surrounding the fuse.

The equations describing the pinch-off of the fuse are

$$\frac{dh}{dt} = \frac{ux}{w} - \frac{fh^4}{\eta w^2}, \tag{5}$$

TABLE I. Values of parameters used in simulations. (T_{m2} values include superheating.)

Parameter	Value
R_t	5 Ω
T_{m1}	1700 K
η	10 Pa
n_q	3.16×10^{10} C m^{-3}
g	0.2
σ_0	3.33 Ω^{-1} m^{-1}
T_{max}	1400 K
T_0	300 K
α	6.89×10^{-7} K^{-2}
C_1	1.66×10^6 J m^{-3} K^{-1}
C_2	3.09×10^8 J m^{-3} K^{-1}
ΔH_1	4.15×10^9 J m^{-3}
ΔH_2	8.30×10^{10} J m^{-3}
δT	50 K
k_3	1.5 W m^{-1} K^{-1}

Property	(a)	(b)	(c)
a_1 (μm)	0.15	0.15	0.15
a_2 (μm)	0.15	0.15	0.15
b (μm)	0.6	0.6	0.3
c (μm)	3	3	1.5
d (μm)	0.3	0.3	0.15
x (μm)	0.1	0.1	0.08
V (V)	5	6	4.8
T_{m2} (K)	2400	2500	2500

$$\frac{dw}{dt} = \frac{fh^3}{\eta w}. \tag{6}$$

The first equation expresses conservation of volume, the second is a crude balance between work done by body forces and work done against friction in the silica. Flow is only allowed to occur once T_{m2} has been exceeded. To allow the equations to be solved numerically h and w are initialized with small nonzero values.

The equations were solved numerically using a fourth order Runge–Kutta scheme with adaptive time-stepping. Parameter values used in the simulations are summarized in Table I. Simulation results with and without superheating of the silicide are compared with experimental data in Fig. 2. Considering the simplicity of the model the results are remarkably good and trends with voltage and fuse size are correctly predicted.

A zero-dimensional, lumped parameter model of the programming of polycrystalline silicon fuses reproduces the available experimental data for one type of fuse. The model captures trends with voltage and size. This strongly suggests that the assumptions used to construct the model are fundamentally correct. To take the model further, more experimental data are required, describing the temperature dependent conductivity of the individual polycrystalline silicon and tungsten silicide layers, for example. This will allow three-dimensional modeling of the partial differential equations describing the system.

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