Electrically Programmable Fuse (eFUSE) Using Electromigration in Silicides

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***Abstract*—For the first time we describe a positive application of electromigration, as an electrically programmable fuse device (eFUSE). Upon programming, eFUSE's show a large increase in resistance that enable easy sensing. The transient device characteristics show that the eFUSE stays in a low resistance state during programming due to the local heating of the fuse link. The programming is enhanced by a device design that uses a large cathode which increases the temperature gradient and minimizes the effect of microstructural variations.**

***Index Terms*—CMOS integrated circuits, DRAM chips, electromigration, fuses, redundancy, tuning.**

I. INTRODUCTION

ELECTROMIGRATION has been studied widely to explain the failure of metal lines in microelectronic devices. Silicides are thought to be more robust than metals with regard to electromigration, resulting in their widespread use as local interconnects and in contacts to p^+ and n^+ diffusion regions. With continuous scaling of device dimensions, electromigration failures have been observed even in silicided contacts [1] and most effort has been focused on alleviating such failures. For the first time, we demonstrate a positive application of electromigration, as an electrically programmable device in advanced CMOS technology.

Fuse devices are useful in CMOS chips for redundancy implementation in memory arrays, for trimming resistors, capacitors and other discrete components in analog circuits, for permanently holding information such as "chip-id" etc. A typical implementation is a laser-fuse, where laser energy is used to evaporate metal links and the resulting resistance change is sensed using a latch. This device pitch is not scalable below the wavelength of the laser beam, typically 1.06 μm, resulting in excessive use of chip area. This approach limits the choice of inter-level dielectrics and metal interconnects. Also, it is preferable to have the option to program these devices after packaging the chip, a feature not possible with laser fuses. In this investigation, we present a novel electrically programmable fuse element (eFUSE) that utilizes electromigration in silicided polysilicon.

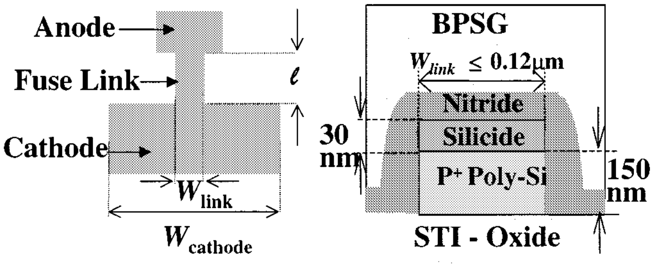

Fig. 1. The top view and cross section of eFUSE. This structure was realized using the standard gate-stack in 0.12 μm CMOS technology without any additional process steps. Experimentally the optimum value of ℓ was found to be 1.2 μm.

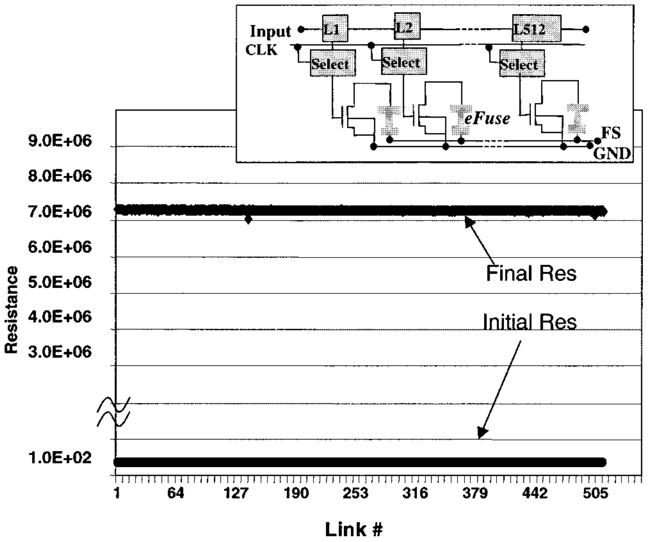

Fig. 2. The initial and final resistance of a group of 512 fuses. The fuses were programmed using a gate pulse of 200 μs duration and 1.5 V magnitude with FS at 3.3 V. The resistances were measured by selecting an individual gate and applying a dc voltage at FS.

II. STRUCTURE AND PROGRAMMING

The top-view and the cross section of eFUSE are shown in Fig. 1. This structure can be realized in a standard CMOS process flow without any additional steps. This structure is typically programmed using a standard NFET in conjunction with appropriate select circuitry as shown in the circuit in Fig. 2. Loading a specific latch with a "1" and applying a clock pulse of 200 μs generates a gate pulse of 1.5 V at the NFET, resulting in a pulse of current through the eFUSE. The peak value, limited largely by the size of the NFET, is 10 mA with FS at 3.3 V in this circuit. The dc resistances were measured by selecting each individual gate along with a dc voltage at

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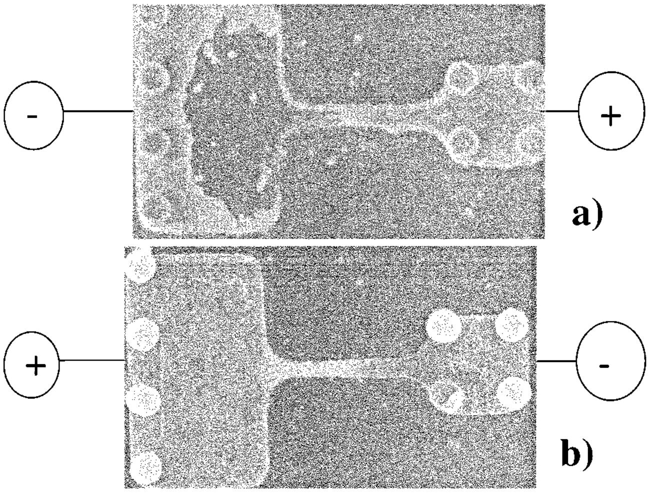

Fig. 3. Top view SEM's of eFUSE under two polarities: (a) larger electrode is the cathode and (b) smaller electrode is the cathode. The location of depletion reverses when the current direction is reversed and is always found near the cathode. Increasing the size of the cathode relative to the link increases ∇T and thus the amount of depletion.

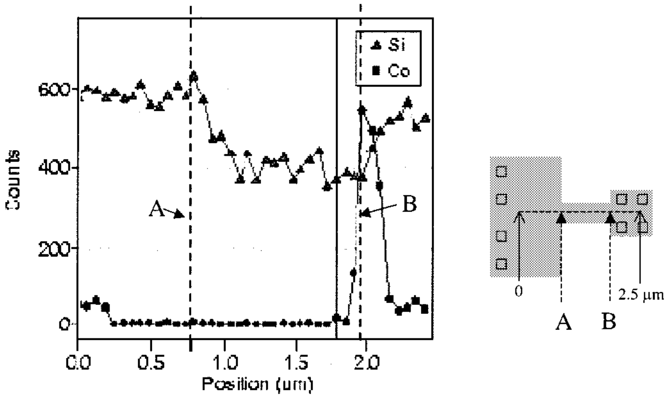

Fig. 4. Energy Dispersive Analysis of X-rays (EDAX) of eFUSE. Line-scan corresponding to the Cobalt and Silicon peaks are shown corresponding to the line indicated in the sketch. A near complete depletion of Cobalt is observed near the cathode and a corresponding accumulation of Cobalt near the anode. The silicon signal strength shows a slight decrease along the link as the excitation volume of the beam is larger than the link.

FS. The observed initial resistance (120 Ω) and final resistance (>7 × 10^6 Ω) are sufficiently far apart for easy sensing (Fig. 2).

The top-view SEM of a discrete eFUSE programmed under two opposing current directions is shown in Fig. 3. The SEM's show depleted regions near the cathode with corresponding accumulations in the anode. This signature is reversed when the current direction is reversed [Fig. 3(b)]. These depleted regions, when examined by Energy Dispersive Analysis of X-rays (EDAX), were found to have practically no Cobalt with a corresponding abundance of Cobalt in the accumulated regions (Fig. 4). When the gate pulse is raised above 1.5 V, the entire structure is ruptured and the location of the rupture is typically in the middle of the link, independent of polarity.

The transient current through the eFUSE was recorded by selecting one eFUSE, with a 10 Ω series resistor at FS and a high bandwidth oscilloscope connected across it (Fig. 5). For a 1.5 V gate pulse, with FS at 3.3 V, the observed current had a peak of 10 mA and continued to flow during the entire duration of the CLK pulse (200 μs). The voltage at the intermediate node, V1, was also measured using a separate channel of the oscilloscope enabling the measurement of the transient resistance of the eFUSE during programming. When the gate pulse voltage is raised above 1.5 V, the current pulse was observed to have a much shorter width, in the range of 1–5 μs and the eFUSE was ruptured.

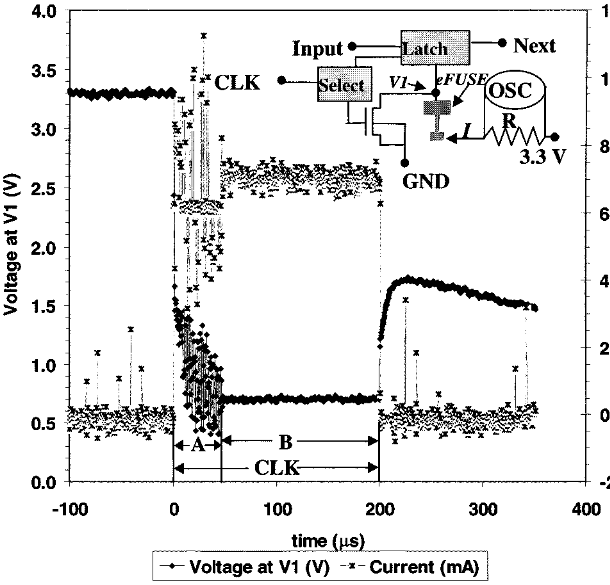

Fig. 5. The transient current through the eFUSE and the voltage at the intermediate node, V1. A gate pulse of 200 μs duration and 1.5 V is applied to the NFET. Although there are some fluctuations in the current during the initial 50 μs (region A) the current is nearly constant during the rest of the time (region B), corresponding to a transient resistance of only 360 Ω. The voltage does not recover to 3.3 V after programming as the applied voltage is divided between the programmed eFUSE (few MΩ final resistance) and the 1 MΩ input impedance of the oscilloscope. The turnaround in voltage exhibited around 220 μs is due to the increasing resistance of the eFUSE as it cools, convolved with the time response introduced by the parasitics present in the circuit.

III. DISCUSSION

The reversal of observed signature with current direction is clear evidence of electromigration. The final resistance is still significantly higher than the resistance expected from the p^+ polysilicon alone, suggesting that the dopant, Boron, has also electromigrated or segregated. This large change in resistance is very desirable for device applications as this significantly reduces the complexity of the sense circuitry. Other modes of increasing the resistance of a poly-silicide links such as thermal rupture or agglomeration [2] do not exhibit consistent behavior and were found to be unstable with thermal cycling. The high final resistance achieved by electromigration also prevents the coupling of significant current during sensing preventing any reversal of programming.

The transient data shows that the current through the eFUSE (Fig. 5), while varying during the initial 50 μs (region A), is nearly constant during the next 150 μs (region B). The link resistance in B is nearly constant at 360 Ω and is lower than the final dc resistance. This is attributed to the high local temperatures achieved at the link, estimated to be in the order of 850 °C

[3][1]. At these temperatures poly-silicon is rendered conductive as it can be expected to become intrinsic with a large carrier concentration. This low resistance state in B allows the eFUSE to couple current for a longer time from the power source, thereby increasing the amount of material electromigrated and the final resistance.

Electromigration based programming, in addition to being least disruptive, is also beneficial for device design as it can be enhanced by suitable choice of geometry. The flux, $\vec{F}$, of migrating species can be written as

$$\vec{F} = N\,\frac{D(T)}{kT} Z * q\vec{E} \tag{1}$$

where N is the atomic density, $D(T)$ is the diffusion coefficient for the migrating species in the host lattice, written as $D_0 e^{-(E_a/kT)}$, $Z^* q$ is the effective charge, and $\vec{E}$ is the local electric field. For electromigration to occur $\nabla.\, \vec{F} \neq 0$. This can be influenced by temperature gradients ($\nabla T \neq 0$) or variations in the microstructure ($\nabla D_0 \neq 0$) [4]. The former is preferable since it has a strong influence on $\vec{F}$ through (1), and is readily controlled through geometry and the power coupled into the structure. Microstructure variations are difficult to control, particularly in small line-width structures where the device dimensions are on the order of the grain size in polysilicon. In eFUSE (Fig. 1), the cathode is chosen to be larger than the link region, resulting in a larger ∇T between the cathode and the link. This effect is also evident in Fig. 3(a), where the depletion of cobalt is larger as there is a bigger ∇T. The link-length also plays a role in ∇T since the ends of the link are the sources of heat loss from the link. The optimal length for this device shape and layer thickness was experimentally determined to be 1.2 μm. The same phenomena were observed even when the link was formed using tungsten silicide.

These eFUSE elements were implemented for invoking redundancy in a 16 Mb embedded DRAM chip and successfully passed a series of rigorous reliability tests for both the programmed and unprogrammed eFUSE's. This implementation also resulted in significant area savings when compared to laser fuses. eFUSE's are also expected to find applications in field programmable arrays and for circuit trimming applications.

ACKNOWLEDGMENT

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REFERENCES

[1] J. S. Huang, H. K. Liou, and K. N. Tu, "Polarity effect of electromigration in Ni_2Si contacts on Si," *Phys. Rev. Lett.*, vol. 76, no. 13, pp. 2346–2349, 1996.

[2] M. Alavi, M. Bohr, J. Hicks, M. Denham, A. Cassens, D. Douglas, and M.-C. Tsai, "A PROM element based on salicide agglomeration of poly fuses in a CMOS logic process," in *IEDM Tech. Dig.*, 1997, pp. 855–858.

[3] E. G. Colgan, J. P. Gambino, and Q. Z. Hong, "Formation and stability of silicides in polycrystalline silicon," *Mat. Sci. Eng.*, vol. 16, no. 2, pp. 43–96, 1996.

[4] S. S. Iyer and C. Y. Wong, "Grain growth study in aluminum films and electromigration implications," *J. Appl. Phys.*, vol. 57, no. 10, pp. 4594–4598, 1985.

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[1] TEM pictures of eFUSE show grain growth of the polysilicon. This requires the link to reach at least the deformation temperature of CoSi2.