# Random Telegraph Noise in 1X-nm CMOS Silicide Contacts and a Method to Extract Trap Density

Min-Cheng Chen, Chia-Yi Lin, Bo-Yuan Chen, Chang-Hsien Lin, Guo-Wei Huang,
Chia-Hua Ho, Tahui Wang, Chenming Hu, and Fu-Liang Yang

***Abstract*—The behavior of random telegraph noise was affected by nickel silicide barrier height engineering in advanced nano-CMOS technologies. Contact resistance fluctuations with magnitude of up to 40% were observed when a Schottky barrier was reduced to 0.2 eV. The large contact resistance instability is attributed to the barrier modification by positive charge trapping and detrapping in a Schottky contact. The prevalence and magnitude of the noise are dependent on the contact area, trap density, trap energy, and the silicide Schottky barrier height. In this letter, we propose a fast method to extract the density of responsible contact traps.**

***Index Terms*—Contact resistance, Poisson distribution, random telegraph noise (RTN), silicide-process-induced traps.**

## I. INTRODUCTION

SILICIDE contact resistance is a considerable bottleneck for achieving high-drive-current FETs at the 20-nm technology node and beyond [1]. Recent reports have indicated that variable silicide barrier height engineering is widely explored to reduce the parasitic resistance [2]. The effective reduction of a Schottky barrier height (SBH) is a direct solution to contact resistance lowering. However, the barrier height reduction process may incur excess defect traps at the contact junction [3]. Although several studies were performed on the resultant junction leakage current [1], the characterization of the process-induced contact traps was not been reported.

Random telegraph noise (RTN) in the current of a MOSFET [4] was explored to characterize Si/SiO$_2$ surface traps [5], traps in high-$k$ gate dielectrics stack [6], and traps in a floating-gate NAND memory device [7]. The RTN phenomenon in p-n junction leakage current [8] was also investigated. This letter reports RTN in contact resistance, which was used to investigate the traps in the Schottky barrier in small nickel silicide (NiSi/Si) contacts. The physical mechanism of RTN in small silicide contacts is proposed, and the silicide trap density is extracted from RTN.

## II. DEVICE FABRICATION

The nickel silicide contact was fabricated in N-type bulk Si (100) wafers. The test pattern design rule is for the 20-nm CMOS technology. Standard $H_2SO_4/H_2O_2$ dilute HF dip was performed for wafer surface pretreatment before Ni deposition. The first silicide anneal was used to form the Ni$_2$Si phase, followed by selective Piranha etching and removal of unreacted Ni. Subsequently, high-resistivity Ni$_2$Si phase was transformed into a low-resistivity NiSi phase with the second rapid thermal annealing. To reduce the silicide Schottky contact barrier height, two distinct barrier-height-reducing treatments were studied in splits B and C. Devices without the barrier-height-reducing treatment (split A) were also fabricated as a reference. To avoid Ni diffusion, the first anneal was replaced by milisecond anneal in split C. According to the thermionic emission model, the Arrhenius plot of the reverse current was used to extract the NiSi/Si effective SBH. The Schottky barrier was reduced from 0.6 (split A) down to 0.4 (split B)/ 0.2 eV (split C).

## III. RESULT AND DISCUSSION

### A. Noise Time-Domain Investigation

Time-domain measurements were performed with an Agilent B1530A semiconductor device analyzer. Contact resistance was measured in 0.1-ms measurement duration at all conditions. Contact resistance fluctuations versus time are shown in Fig. 1 for a small contact size ($1\ \mu\text{m} \times 1\ \mu\text{m}$) (20 000 sampling points were used). Forty test devices were measured. A considerable percentage of the small-area samples (approximately 14 devices) exhibited obvious two-level RTN [see Fig. 1(a)], whereas the others did not [see Fig. 1(b)]. The multiple-level noise behavior did not occur in larger devices at similar current density. Three current behaviors were observed in the NiSi/Si contacts. Several contacts exhibited a single higher level of current. A smaller number of contacts exhibited a single lower level of current. The remainder of the devices exhibited two-level noise jumping between those two higher and lower current levels.

The two-level contact resistance is explained with the model shown in Fig. 2. If a trap in the Schottky barrier is occupied by a positive charge, it has the same effect as an extra acceptor ion, and the current increases because of the lowering of the tunneling barrier [see the dotted lines in Fig. 2(a)]. When a trap contains several kiloteslas above $E_f$ [see Fig. 2(a)], the trap is almost always devoid of electrons and is positively charged, and the current remains at the high level. When a contact contains

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M.-C. Chen, C.-Y. Lin, B.-Y. Chen, C.-H. Lin, G.-W. Huang, C.-H. Ho, and F.-L. Yang are with the National Nano Device Laboratories, Hsinchu 30078, Taiwan (e-mail: ncchen@ndl.narl.org.tw).

T. Wang is with the Department of Electronics Engineering, National Chiao-Tung University, Hsinchu 300, Taiwan.

C. Hu is with the Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA 94720-1770, USA.

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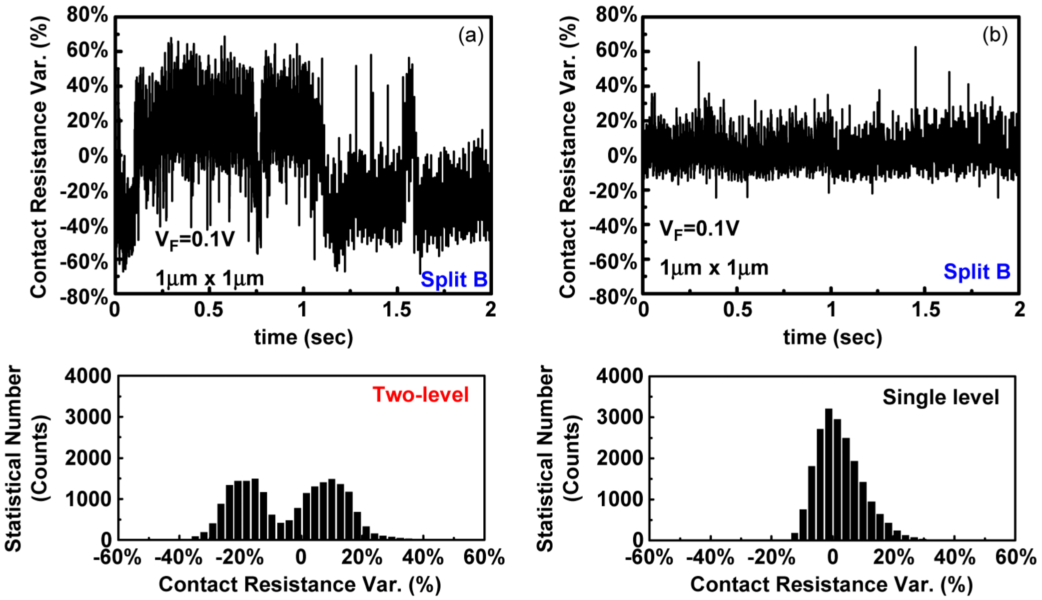

Fig. 1. Time-domain contact resistance measurements of small-area silsicide contacts. (a) Some test devices show two-level RTN behaviors. (b) Others do not.

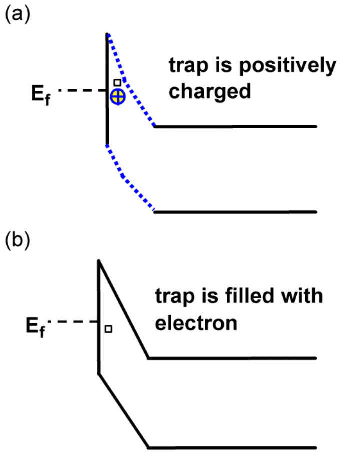

Fig. 2. Schematic energy-band diagrams of a Schottky contact exhibiting (a) high level of current as a trap is positively charged. (b) Low level of current as a trap is filled with an electron.

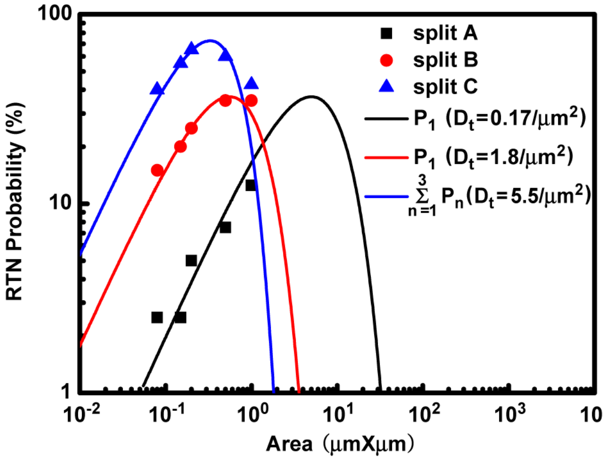

Fig. 3. Probabilities of samples exhibiting RTN behaviors for various contact areas and three silicide process splits.

a trap with several kiloteslas below $E_f$ [see Fig. 2(b)], it is almost always neutral (or negative), and the current remains at the lower level. The current will hop between a higher level and a lower level only when a contact contains a trap near (within a couple of kiloteslas from) $E_f$ and when the trap is empty of electron (positive) part of the time and filled with electron (neutral or negative) part of the time, as determined by the Fermi–Dirac statistics [4].

### B. Trap Density Extraction

Fig. 3 shows the statistical probabilities of samples exhibiting RTN behaviors at various contact areas for the three silicide process splits. For every size/split combination, statistical data were acquired on 40 test devices from the same wafer. The noise occurrence probability was strongly dependent on the silicide splits and the contact area. We believe that split A has a low percentage of contacts exhibiting RTN because it did not receive the barrier lowering treatment and had the lowest density of traps; therefore, most split A contacts did not have any trap near $E_f$. Split C received the most additional barrier reduction process steps, which produced the largest trap density and, therefore, the largest incidences of RTN.

At sufficiently large contact area (1 $\mu\mathrm{m}^2$ in Fig. 3), a relatively large percentage of even split-A contacts contained a trap near $E_f$ and therefore exhibited RTN in contact resistance. In split C, which had the largest trap density, the percentage of contact exhibiting visibly random RTN began to decrease when the contact size exceeded approximately 0.1 $\mu\mathrm{m}^2$. This was expected because RTN is difficult to observe when more than one or two traps are present in the same device. This is the same reason that the RTN is observed only in small MOSFETs [4].

The RTN occurrence probability is the probability for a contact to contain one or more traps (near $E_f$). This probability can be predicted by the binomial Poisson distribution [9]. If the traps (near $E_f$) are uniformly and randomly distributed with

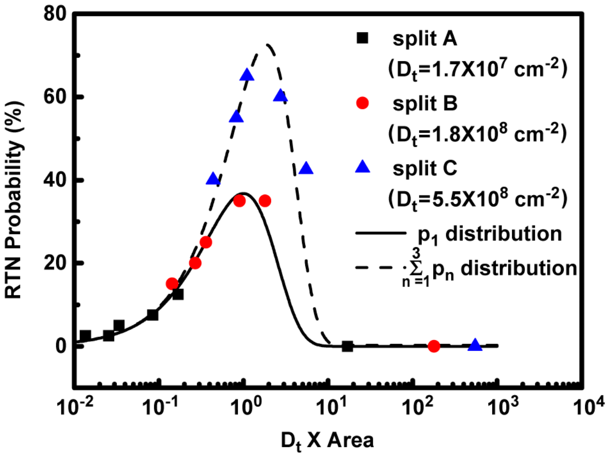

Fig. 4. Cumulative probabilities of samples with observing RTN behaviors could be projected by the Poisson distribution of single-trap/multitrap occupancy.

trap density $D_t$, the probability of a contact with area Area containing $n$ traps ($n$ being 0, 1...) is

$$P_n = \frac{(D_t \times \text{Area})^n}{n!} e^{-(D_t \times \text{Area})}. \tag{1}$$

When $P_n$ is summed over all possible values of $n$, it is equal to unity as follows:

$$\sum_{n=0}^{\infty} P_n = 1. \tag{2}$$

The data in Fig. 3 are fitted to three $P_n$ curves [see (1)] with $D_t$ chosen to fit the data. As expected, split A has the lowest $D_t$, and split C has the highest $D_t$. $P_1$ (RTN cannot be observed with two or more traps) seems to efficiently fit splits A and B. The peak value of 80% of Split C optimally fitted with $P_1 + P_2 + P_3$ (RTN can be observed even with three traps in a contact [10]) because splits B and A must be statistically 3 or 30 times larger in area than split C to contain the two or the three traps. Their base current would be 3 or 30 times larger, the magnitude of the RTN signal relative to the base current would be 3 or 30 times smaller, and the detection software (based on relative fluctuation magnitude) would underreport the RTN probability. Fig. 4 replots the same data and theory, as in Fig. 3, but in linear probability scale and against $D_t \times$ Area. The probability of contact resistance exhibiting RTN decreases to zero in a large contact. RTN contact resistance is a unique phenomenon to small-scale contacts. The multiple-level RTN contact resistance noise were only observed in the intermediate area range. Appropriate contact area may effectively improve contact resistance variation from RTN suppression.

## IV. CONCLUSION

In summary, a new RTN measurement was used to identify the process-induced traps in small NiSi/Si contact for the first time. The noise in contact resistance was attributed to positive charge trapping and detrapping and the resultant Schottky barrier current (resistance) modulation. The designs of processes to produce lower SBH were revealed to create higher trap density and higher incidences of contact resistance RTN. Furthermore, we demonstrated that RTN occurrence probabilities follow the binomial Poisson distribution and present a new method for inline and nondestructive measurement of noise-generating traps in the small silicide contacts.

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