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Eigenanalysis of morphological diversity in silicon random nanostructures formed via resist collapse

Makoto Naruse [a,*], Morihisa Hoga [b], Yasuyuki Ohyagi [b], Shumpei Nishio [b], Naoya Tate [c], Naoki Yoshida [d], Tsutomu Matsumoto [d,e]

[a] *Network System Research Institute, National Institute of Information and Communications Technology, 4-2-1 Nukui-kita, Koganei, Tokyo 184-8795, Japan*

[b] *Dai Nippon Printing Co. Ltd., 250-1 Wakashiba, Kashiwa, Chiba 277-0871, Japan*

[c] *Graduate School of Information Science and Electrical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan*

[d] *Graduate School of Environment and Information Sciences, Yokohama National University, 79-7 Tokiwadai, Hodogaya, Yokohama 240-8501, Japan*

[e] *Institute of Advanced Sciences, Yokohama National University, 79-5 Tokiwadai, Hodogaya, Yokohama 240-8501, Japan*

HIGHLIGHTS

- Eigenanalysis of random nanostructures reveals identities' capacity.
- Unified model considers morphological diversity and measurement stability.
- Nanoscale morphology exhibits great potential for security applications.
- The proposed eigenanalysis strategy is applicable to other material architectures.

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ABSTRACT

Nano-artifact metrics is an information security principle and technology that exploits physically uncontrollable processes occurring at the nanometer-scale to protect against increasing security threats. Versatile morphological patterns formed on the surfaces of planar silicon devices originating from resist collapse are one of the most unique and useful vehicles for nano-artifact metrics. In this study, we demonstrate the eigenanalysis of experimentally fabricated silicon random nanostructures, through which the diversity and the potential capacity of identities are quantitatively characterized. Our eigenspace-based approach provides intuitive physical pictures and quantitative discussions regarding the morphological diversity of nanostructured devices while unifying measurement stability, which is one of the most important concerns regarding security applications. The analysis suggests approximately 10^{115} possible identities per 0.18-μm^2 nanostructure area, indicating the usefulness of nanoscale versatile morphology. The presented eigenanalysis approach has the potential to be widely applicable to other materials, devices, and system architectures.

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[*] Corresponding author.
E-mail addresses: naruse@nict.go.jp (M. Naruse), houga-m@mail.dnp.co.jp (M. Hoga), Ooyagi-Y@mail.dnp.co.jp (Y. Ohyagi), nishio-s3@mail.dnp.co.jp (S. Nishio), tate@ed.kyushu-u.ac.jp (N. Tate), yoshida-naoki-dk@ynu.jp (N. Yoshida), tsutomu@ynu.ac.jp (T. Matsumoto).

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1. Introduction

Artifact metrics [1], also called physical unclonable functions (PUF) [2], utilize the unique physical properties of individual objects for authentication and clone resistance purposes in information security applications. These include electromagnetic [3], mechanical, and optical properties [4] associated with the objects such as ordinary paper [5], paper containing magnetic microfibers [6], plastics, and semiconductor chips. Matsumoto et al. demonstrates *nano-artifact metrics* that exploits physically uncontrollable processes occurring at the nanometer-scale, which are well beyond the scope of nanostructure technologies, in order to protect against increasing security attacks [7]. Versatile, nanoscale morphological patterns formed on the surfaces of planar silicon devices are one of the most unique and useful vehicles for nano-artifact metrics. This study investigates morphological diversity in silicon random nanostructures based on the eigenanalysis approach.

In particular, we utilize the random collapse of resists induced by exposure to electron-beam (e-beam) lithography [7]. Resist collapse may occur during the rinse process of lithography, and depends on the pattern resolution, resist thickness, and duration of e-beam exposure [8]. The result is the collapse of the intended pattern and production of versatile morphological patterns with minimum dimensions smaller than the resolutions of nanofabrication technologies [7]. The wafer is then etched with HBr-based gas using inductively coupled plasma (ICP)-type reactive ion etching, and the resist is stripped by oxygen ashing. The basic performance based on the resultant silicon nanostructures for security applications was clarified in Ref. [7] by quantitatively evaluating the false-match rate (FMR) for verifying identities, the false non-match rate (FNMR) for characterizing the stability of measurements, and the clone-match rate for evaluating the difficulties in making clones.

However, the physical limitations of such an approach are not completely known yet, especially in terms of the number of different devices or identities that could be distinguished based on the nanoscale morphological patterns. This is especially important in view of future applications such as document security [9] and Internet-of-Things (IoT) [10], where securing identities of massive number of devices is critical. In this study, we demonstrate eigenanalysis of experimentally fabricated silicon random nanostructures, through which the diversity and the potential capacity of identities are quantitatively characterized. Our eigenspace-based approach provides intuitive physical pictures and quantitative discussions regarding the morphological diversity of nanostructured devices while uniting measurement stability, which is one of the important concerns for security applications.

2. Experimental devices

First, we review the experimental random nanostructured devices analyzed in this study. We fabricated an array of resist pillars with a 60 nm × 60 nm × 200 nm cross-sectional area on a grid of 120 nm × 120 nm squares that filled a 2 μm × 2 μm square, as shown in Fig. 1(a). We used an e-beam lithography system (JEOL JBX-9300FS) with a 100-kV acceleration voltage. In the rinse process, the random collapse of resist pillars was induced as shown in the scanning electron microscope (SEM) image in Fig. 1(b); versatile morphological patterns or structural fluctuations were observed. The silicon nanostructured patterns obtained after the etching and resist removal processes were imaged by a critical-dimension SEM (CD-SEM, Hitachi High-Technologies CG4000). We analyzed 2383 samples fabricated on a single 200-mm–diameter wafer. Fig. 1(c) and (d) shows examples of SEM images of an array of collapsed resist pillars. The image contains 1024 × 1024 pixels and has an 8-bit resolution (256 levels). Versatile morphologies were observed, and the structural detail of the patterns (Fig. 1(c)) is as small as 9.23 nm [7].

3. Results and discussion

We examine experimentally observed structural diversity based on the following eigenspace-based principle. An 8-bit (256 levels) grayscale image of size 128 × 128 pixels was extracted from around the center of a pillar array image and smoothed using an 11 × 11 median filter. Here, one pixel occupies an area of approximately 3.3 nm side-length; therefore, the area of a single image is about 0.18 μm^2. We denote an image by a vector $\boldsymbol{x}_i$, which has $P = 128 \times 128$ elements. All the images or the total sets of devices are summarized by a matrix

$$Z = \{\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots, \boldsymbol{x}_N\}, \tag{1}$$

where N is the number of devices, which is 2383 in the present study. Let the mean values of all images be given by

$$\boldsymbol{\mu} = \frac{1}{N}\sum_{i=1}^{N} \boldsymbol{x}_i. \tag{2}$$

The covariance matrix is given by

$$C = \frac{1}{N}(Z - \boldsymbol{\mu})^T (Z - \boldsymbol{\mu}), \tag{3}$$

where T indicates the matrix transpose and $(Z - \boldsymbol{\mu})$ implies subtracting the vector $\boldsymbol{\mu}$ from each column of matrix Z. By solving the eigenequation

$$C\boldsymbol{s}_k = \lambda_k \boldsymbol{s}_k, \tag{4}$$