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Zinc Oxide Random Laser as Physical Unclonable Function

Jonathan Andreasen †
Cybersecurity, Information Protection, and Hardware Evaluation Research Lab
Georgia Tech Research Institute
Atlanta, GA USA
jonathan.andreasen@gtri.gatech.edu

David A. Scrymgeour
Microsystems Assessment
Sandia National Laboratories
Albuquerque, NM USA
dscrymg@sandia.gov

Roger Brown
Cybersecurity, Information Protection, and Hardware Evaluation Research Lab
Georgia Tech Research Institute
Atlanta, GA USA
roger.brown@gtri.gatech.edu

ABSTRACT

We aim to enhance the security of optical physical unclonable functions (PUFs). It has been shown possible to reconstruct an input signal across a highly scattering sample through partial measurements of the transmission matrix, making the traditional optical PUF vulnerable to attack. Random lasers frustrate this type of attack, due to the nonlinear interaction of modes. At the same time the strength of the original optical PUF, which comes from the practical infeasibility of cloning many randomized scatterer locations, is preserved. PUFs must also be reliable and demonstrate repeatability, which is challenging in random lasers that typically exhibit shot-to-shot varying emission spectra. Therefore, we develop random laser films with the goal of shot-to-shot stability.

CCS CONCEPTS

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KEYWORDS

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1. Introduction

Random laser emission is easily evaluated, but physical reproduction of the device is practically infeasible and indirect evaluation is frustrated by nonlinear interactions. Random lasers achieve lasing action by replacing the traditional optical cavity with a multiple-scattering medium [4]. With an optical gain material present, input energy is supplied until the gain compensates loss due to leakage and absorption. Due to the open nature of random lasers, leakage loss rates are typically high so that large pumping rates are required to reach the lasing threshold. Also because of cavity openness, modes are not orthogonal but bi-orthogonal and overlap both spatially and spectrally [2]. In addition to the strong gain, this overlap results in mode competition and, consequently, nonlinear interaction as the pumping rate is increased above the threshold [13]. We will take advantage of this nonlinearity as a means of providing security, reinforcing the unclonable feature of this PUF.

Nonlinearity in this PUF competes directly with repeatability and reliability. Small changes during laser buildup, caused by spontaneous emission, for example, can result in different lasing states achieved under identical experimental conditions [8]. We avoid such volatility by focusing on random laser films that have demonstrated some stability in shot-to-shot spectra. Nano-crystalline Zinc oxide (ZnO) [7] has demonstrated a limited capacitance for repeatable emission spectra. Moreover, these films offer tunability via grain size. Since scattering occurs primarily at grain boundaries, adjusting grain sizes changes the mean free path and, effectively, the scattering strength is altered. Underlying randomness in grain orientation, with grain sizes less than one micrometer, is generated naturally during the fabrication process. Precise cloning of every grain, its size, orientation, and position within the film is infeasible, practically speaking.

As will be shown, modeling this PUF requires an accounting of all spatial information due to the coherent buildup of light in resonances of the scattering medium. Since the film is unclonable, so also is obtaining such information for precise simulations mimicking the physical system. However, the qualitative behavior of the film demonstrating nonlinearity will be demonstrated.

2. Film fabrication

Our technical approach is to develop polycrystalline films of ZnO with quenched disorder that are conformal, environmentally stable, and applicable to a variety of substrates and surfaces. Because random lasers have not yet been implemented as PUFs, it is somewhat unclear what the optimal material parameters should be. Based on previous random lasing results [7] we are interested in grain sizes from 30 – 500 nm. We therefore investigated films grown by multiple techniques including sputtering, atomic layer deposition (ALD), sol-gel thin film deposition. Basic XRD of all the films indicate ZnO which can vary between well oriented c-axis ZnO columnar growth for the sputtered and sol-gel material, to more mixed platelet type growth modes for the ALD, shown in Figure 1, indicating that growth parameters can be tweaked to modify the resulting film microstructure, which can be an important property for the random lasting.

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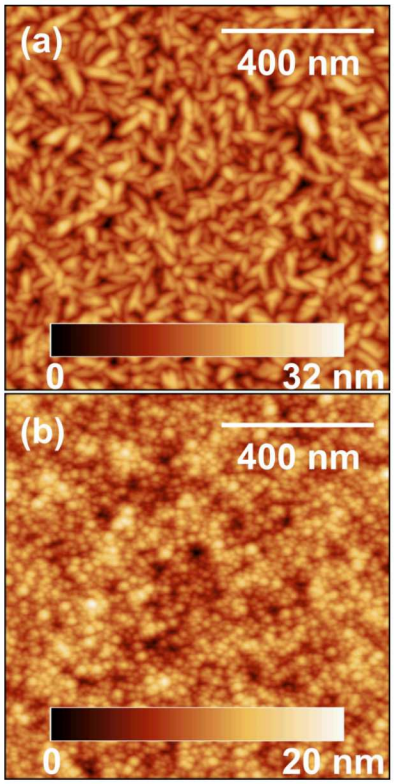

Figure 1: AFM topography image showing platelet topography of ALD deposition of ZnO compared to (b) columnar topography of the sol-gel deposition of ZnO.

Shown in Fig. 1 are two different ZnO morphologies realized by ALD compared to sol-gel deposition characterized by atomic force microscopy (AFM). Both films have very smooth and comparable surface roughness, important for the generation of random lasing, with the ALD system having root mean square roughness of 3.7 ± 0.1 nm compared to the sol-gel deposition with 2.1 ± 0.1 nm. The grain size in each are small with a mean grain size of 32.4 nm for the ALD and 24.9 nm for the sol-gel film determined. These both highlight the inherent randomness in the films.

3. Optical experiments

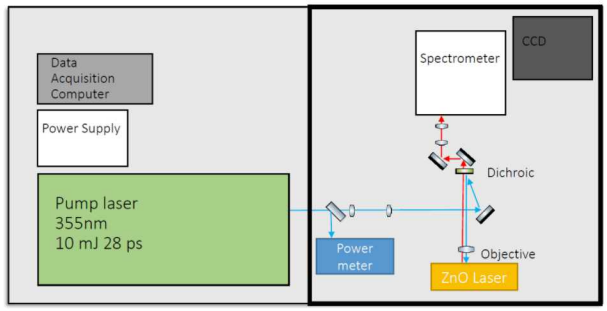

Figure 2: Key elements of the experimental layout: pulsed lump laser, steering and mode matching optics, grating spectrometer and CCD camera.

The goal for the optical experiment is to direct an input signal, in this case the pump laser pulse, onto the PUF film, which returns a unique key. The key shall be obtained from the random laser speckle pattern similar to the original optical PUF [10]. In addition to incidence angle of the pump beam, other degrees of freedom include the intensity, spatiotemporal profile (e.g., [3]), and location of the pump beam. These degrees of freedom contribute to the total size of the signal-key pair space but shall also require significant engineering for repeatable control. As a step toward this goal, we have measured the fluorescence spectrum of ZnO, which validates the optical design.

The experimental setup is shown in Fig. 2. The fluorescence is collected through the pump-focusing objective and is separated from the pump light using a long-pass dichroic. It is then mode matched to a grating based spectrometer (Oriel 860). The light from the spectrometer output port is imaged onto a peltier cooled CCD camera (Princeton Instruments Photon Max 512B). These spectrometer images encode spectral information along the horizontal axis as well as spatial information along the vertical axis of the film.

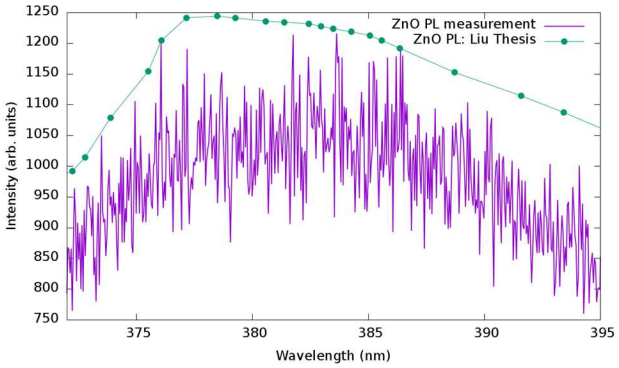

Figure 3: Photoluminescence of ZnO film compared against extracted data from Ref. [7].

The measured fluorescence is shown in Fig. 3. A LED at 365 nm pumps the film above the ZnO band gap. The film emission is spectrally separated from the pump light using a long-pass dichroic at 370 nm, coupled in to a grating spectrometer, and imaged on to the CCD camera. The grating spectrometer is calibrated using two independent diode lasers at 426.17815 nm and 403.331 nm. The former is referenced to the atomic Cs D2 line via saturated absorption spectroscopy and a transfer cavity lock. The latter is a free running diode. Both lasers were simultaneously measured on a High Finesse WS-8 wavemeter. Good agreement with the spectrum extracted from data in Ref. [7] validates the experimental setup.

Random lasing must be initiated using much higher intensities. The third harmonic at 355 nm of a high-power, pulsed laser (Ekspla PL 2230) will be steered and focused onto the ZnO film. The relatively short-time excitations limit the total energy supplied to the film and, therefore, limit film degradation and bleaching. The short times also prevent unexpected temporal profiles generated by longer nanosecond pulses from inducing chaotic effects, rogue waves, and coherent instabilities, such as the Lorenz-Haken. Emission from the laser film upon each pump pulse can persist for microseconds, so enough time must exist between pulse shots to avoid unexpected interference; a 50 Hz repetition rate will be used.

4. Numerical simulations

Here, we numerically investigate the nonlinearity of two-dimensional random lasers by progressively increasing the external pump intensity. We solve Maxwell's equations directly without approximation using the finite-difference time-domain (FDTD) method [12]. The gain medium in FDTD is modeled by a four-level atomic system coupled to the light field via polarization [9]. Large gain, which must be introduced in order to counterbalance the large loss of the system, leads to a nonlinear evolution of the lasing mode amplitudes as a function of the pumping rate.

Each FDTD simulation with a fixed value of the pumping rate initializes the atomic populations to the stationary values in absence of stimulated emission. Then a small-intensity, broadband light pulse is launched, which propagates and is scattered, providing the nonzero initial field necessary for lasing action to begin. If the pumping rate is larger than the threshold value, the laser field builds up until it reaches a value where the population inversion starts to be depleted by increasing stimulated emission. The steady-state regime is reached when the value of the population inversion density corresponds to the gain, which exactly compensates the loss through leakage. This is standard behavior in any laser oscillator.

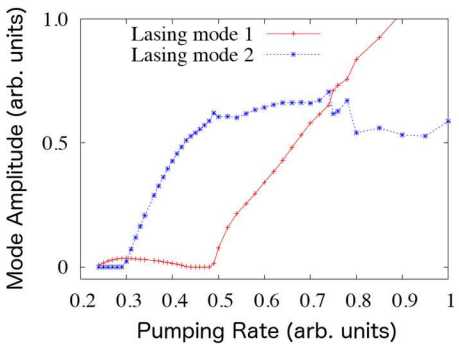

Figure 4: Numerical demonstration of nonlinearity via two-mode competition for optical gain.

Two modes of a random laser near threshold are considered in Fig. 4. Mode 1 is the first lasing mode at threshold. As mode 2 begins lasing, the amplitude of mode 1 is strongly reduced until it is suppressed. As further nonlinear changes take place in the medium, mode 1 is revived and similarly reduces the amplitude of mode 2. Random lasers in reality typically exhibit many more modes that interact in similarly unexpected ways.

5. Conclusions

Characterizations of the ZnO film demonstrate the tunable nature of our approach to enhancing optical PUF security. Fine tuning the scattering system and making adjustments based on feedback from results of the optical experiment will be crucial for PUF realization. The numerically demonstrated nonlinearity intrinsic to random lasers also demonstrates their potential.

However, Herder *et al.* [6] call out separability and calibration of the input location as other difficulties with the optical PUF. The original PUF could easily be detached and applied to counterfeit devices if intercepted by attackers. Random laser film can be grown directly on many surfaces, such as a printed circuit board [5], plastic syringes or tissue paper [11]. Removing the film without altering the scattering structure is expected to be infeasible but remains to be tested. Nevertheless, applying the film as a continuous layer around the device may offer more protection against this attack. Importantly, because signal-key verification needs to be repeatable, a method of indexing excitation locations on the film will be incorporated during fabrication. One extreme is to segment the film into patches with index marks identifiable from a microscope integrated onto the substrate surface. Gaps between patches would be large enough to avoid cross-talk. However, such small and clearly definable patches might be much easier to clone. These difficulties, while critical to address, do not appear to be fundamental conceptual problems with the optical PUF.

Although a specific film is proposed here with favorable properties, the random laser PUF mechanism is independent of material composition. Therefore, the random laser PUF could

conceivably be expanded to different materials and functionalized for specific target applications.

Because the signal-key pair is sensitive to the scatterer configuration, as is true of most optical PUFs, this device also has potential anti-tampering applications. For example, any significant mechanical pressure will alter the system enough for emission to be noticeably different. Other forms of tampering include chemical and thermal attacks [1] and advanced techniques may include high frequency irradiation. For each application, the target operating conditions must be weighed against the possible attacks in order to choose an appropriate material for the film.

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