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Jonathan Roberts

Using Imperfect Semiconductor Systems for Unique Identification

Doctoral Thesis accepted by the
Lancaster University, UK

Springer

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Supervisor's Foreword

I am delighted that Springer is publishing this outstanding thesis by Jonathan David Roberts. It develops and explores a novel solution to the age-old problem of authentication. How can we verify that a person, object or transaction is genuine? For every system that has been created to provide an identity, nefarious parties have found ways around. The Internet era has seen signatures replaced by passwords, fingerprints, iris scanners and secure questions, but the threat of identity theft on society has never been greater.

Physical unclonable functions are the hardware realisation of fingerprints; they are objects or devices that produce a unique response, when challenged, which is derived from a complex physical property of a system. These systems remove the need for secrets to be stored in memories and give would-be adversaries the task of trying to produce a clone. Rather than copying data from memory, which is often trivial, an identical clone requires a physical system containing the same, complex, physical properties. This can represent a much greater burden, increasing the security of such systems.

Whilst the principle of the physical unclonable function is interesting, they have not been widely adopted. The technology required to reproduce complex objects is becoming increasingly accessible, making these devices susceptible to counterfeiting. To address this, Jonathan took an important step to leapfrog the capabilities of current and near-future manufacturing processes. He applied a simple quantum technology to produce the first devices producing identities that are sensitive to atomic-scale imperfections.

For many years, Moore's law has driven the miniaturisation of semiconductor fabrication techniques. This has enabled the development of numerous important nanotechnologies, but many of these face a common problem when mass-produced, namely inconsistencies between devices. Small changes in the dimensions and composition of nanostructures lead to macroscopic differences in their performance, due to the quantum mechanical laws governing their behaviour. The real breakthrough in this thesis is the realisation that this nanoscale problem is actually a boon to the field of security. Being able to derive identities from random nanoscale variations creates an almost ideal solution to the challenge of authentication; the technology is simple to produce, easily read and almost impossible to reproduce.

The importance of this breakthrough was recognised by EPSRC's (UK) ICT Pioneers Award, which was presented to Jonathan in 2015, and the many high-quality publications in which Jonathan's scientific results were published.

Lancaster, UK
July 2017

Prof. Robert J. Young

Abstract

The secure identification of an object or electronic system is carried out through the provision of some unique internal or external characteristic. The most obvious examples of these include passwords and fingerprints that can identify a person or an electronic device, and holograms that can tag any given object to provide a check of its authenticity. Unfortunately, modern technology provides resources that enable the trust of these everyday techniques to be undermined.

Identification schemes have been proposed to address these issues by extracting the identity of a system from its underlying physical structure, which is constructed such that the system is hard-to-clone or predict. These systems are known as Unique Objects (UNOs) and Physically Unclonable Functions (PUFs).

The aim of the work in this thesis is to create a novel type of UNO/PUF that utilises the atomic-scale uniqueness of semiconductor devices by measuring a macroscopic quantum property of the system. The variations in these quantum properties are amplified by the existence of such atomic-scale imperfections, meaning these devices would be the hardest possible system to clone, use the least resources and provide robust security. Such devices would be of great societal and political significance and would provide the biggest technological barrier between the good guys and the bad.

Specifically, this work has introduced three distinct devices based on semiconducting systems that could provide atomic-scale unique identification:

- Electronically—Fluctuations in the current–voltage characteristics of Resonant Tunneling Diodes (RTDs) were found to provide a simple measurement of the underlying quantum state electronically.
- Optically—Macroscopic thin films of the two-dimensional material, MoS_2, were created by the Langmuir-Blodgett technique for the first time and have laid the foundations for the formation of an optical analogue of an atomic-PUF/UNO system.

- Optoelectronically—The Langmuir-Blodgett technique's flexibility was utilised to fabricate complex heterostructures that couple graphene to semiconducting nanoparticles. This system should provide an ideal system with efficient electronic and optical characteristics that would be useful in a range of applications, including unique identification.

List of Publications

1. **J. Roberts**, A. Black, B. J. Robinson, P. Tovee, C. S. Woodhead, Y. J. Noori, Y. Cao, R. Bernado-Gavito, and R. J. Young, "*Graphene/Nanoparticle/Graphene Heterostructures Fabricated with the Langmuir-Blodgett Technique*" (Manuscript in preparation, 2016).
2. **J. Roberts**, B. J. Robinson, P. Tovee, C. S. Woodhead, Y. J. Noori, Y. Cao, R. Bernado-Gavito, and R. J. Young, "*Deposition of MoS_2 Nanosheets Using the Langmuir-Blodgett Technique*" (Manuscript in preparation, 2016).
3. R. Bernado-Gavito, **J. Roberts**, J. Sexton, B. Astbury, H. Shokeir, T. McGrath, Y. J. Noori, C. S. Woodhead, M. Missous, U. Roedig & R. J. Young, "*N-State Random Switching Using Quantum Confinement in Diodes*" (under review, Nature Communications, 2016).
4. **J. Roberts**, R. Bernado-Gavito and R. J. Young, "*Generating a Nondeterministic Response to a Challenge*", GB1613002.3 (2016).
5. **J. Roberts**, R. Bernado-Gavito and R. J. Young, "*Generating a Unique Response to a Challenge*", GB1613002.3 (2016).
6. C. S. Woodhead, **J. Roberts**, Y. J. Noori, Y. Cao, R. Bernado-Gavito, P. Tovee, A. Kozikov, K. Novoselov and R. J. Young, "*Increasing the Light Extraction and Longevity of TMDC Monolayers Using Liquid Formed Micro-lenses*", 2D Materials, **4**, 1 (2016).
7. Y. J. Noori, Y. Cao, **J. Roberts**, C. S. Woodhead, R. Bernado-Gavito, P. Tovee and R. J. Young, "*Photonic Crystals for Enhanced Light Extraction from 2D Materials*", ACS Photonics, Article ASAP.
8. **J. Roberts**, U. Roedig and R. J. Young, "*Quantum Physical Unclonable Function*", GB1611554.5 (2016).
9. **J. Roberts**, I. E. Bagci, M. A. M. Zawawi, J. Sexton, N. Hulbert, Y. J. Noori, M. P. Young, C. S. Woodhead, M. Missous, M. A. Migliorato, U. Roedig and R. J. Young, "*Atomic-scale Authentication with Resonant Tunneling Diodes*", MRS Advances, 5 (2016).
10. **J. Roberts**, P. Speed and R. J. Young, "*Using Quantum Effects in Nanomaterials for Unique Identification*", SPIE Newsroom, 3 (2016).

11. **J. Roberts**, I. E. Bagci, M. A. M. Zawawi, J. Sexton, N. Hulbert, Y. J. Noori, M. P. Young, C. S. Woodhead, M. Missous, M. A. Migliorato, U. Roedig and R. J. Young, "*Using Quantum Confinement to Uniquely Identify Devices*", Scientific Reports, 16456 (2015).
12. **J. Roberts**, U. Roedig and R. J. Young, "*Unique Identifier*", GB1406002.4 (2014).
13. M. P. Young, C. S. Woodhead, **J. Roberts**, Y. J. Noori, M. T. Noble, A. Krier, E. P. Smakman, P. M. Koenraad, M. Hayne and R. J. Young, "*Photoluminescence Studies of Individual and Few GaSb/GaAs Quantum Rings*", AIP Advances, 4, 117127 (2014).
14. R. A. Griffiths, A. Williams, C. Oakland, **J. Roberts**, A. Vijayaraghavan and T. Thomson, "*Directed Self-assembly of Block Copolymers for use in Bit Patterned Media Fabrication*", Journal of Physics D, 46, 503001 (2013).

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