Hints from Hardware Security for solving real-world challenges

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Outline

- Introduction to Hardware Security
- What can be done during challenging time of the lockdown
  - direct help: making life better
  - indirect help: encouragement and ideas
- Facing challenges and coming up with workarounds
- Future work
- Conclusion

Introduction

- Hardware Security is important
  - data and IP protection
  - cyber security and preventing attacks on services
  - countermeasures against all known attacks
  - educate hardware engineers
- Hardware Security is about finding flaws and fixing them
  - evaluation of implemented security features and improving them
- Hardware Security challenges
  - new attack technologies
  - modern fabrication processes (7nm, 10nm, 14nm, 28nm, 32nm, 40nm)
  - develop countermeasures through understanding of flaws
  - predict new attack methods
- What could we possibly learn from Hardware Security?
  - innovative approaches to virtually impossible tasks

Introduction

- Senior Research Associate at the University of Cambridge
  - Hardware Security research (attack technologies) since 1995
  - test microcontrollers, smartcards, FPGAs and SoCs for security
  - knowledge: chemistry, electronics, physics (MSc), computer science (PhD)
- Strong track record of new and “impossible” attack methods
  - 1996: clock glitching attacks on security in MC68HC05 and MC68HC11 MCUs
  - 1999: power glitching attacks on security in PIC16F62x/8x and AT90Sxxx MCUs
  - 2002: discovery of optical fault injection attacks shook the industry
  - 2005: prove of data remanence in EEPROM and Flash memory
  - 2006: use for combined attacks of fault injection with power analysis
  - 2009: use of optical emission analysis to complement power analysis
  - 2010: bumping attacks that can extract AES key and data from Flash memory
  - 2012: hardware acceleration to power analysis for finding backdoors
  - 2016: demonstration of “impossible” NAND mirroring attack on iPhone 5c
  - 2016: direct SEM imaging of EEPROM and Flash memory contents
  - 2017: data extraction from encrypted data bus using microprobing attack
  - 2018: live decapsulation carried on a battery powered chip

What can be done during challenging time

- Hardware Security research does not run very well in the lockdown
  - physical devices are not always small
  - sample preparation is sometime a messy process (chemicals, machinery)
  - experimental setup could be bulky or require special environment
- Hardware Security could still help with solving challenges
  - authentication against unauthorised counterfeiting (supply chain security)
  - temporary solutions for authorised authentication (supply chain disruption)
  - build compatible products if normal supply is struggling
- Hardware Security could encourage research in other areas
  - find workarounds if obstacles are encountered
  - bring innovations to new approaches and “impossible” methods
  - come up with new “crazy” ideas
- What could we possibly learn from Hardware Security?
  - innovative approaches to virtually impossible tasks

Direct methods

- Authentication of devices
  - Defence: prevent counterfeit products by improving hardware security
  - Attack: allow legitimate ways of bypassing protection in disrupted supply
- Invasive attacks (high cost and long setup time)
  - silicon deprocessing and reverse engineering
  - microprobing and chip modification
- Semi-invasive attacks (medium cost and setup time)
  - optical imaging and emission analysis
  - optical fault injection
- Non-invasive attacks (low-cost and short setup time)
  - brute forcing
  - side-channel: eavesdropping, timing, power and electromagnetic analysis
  - power glitching and electromagnetic fault injection
  - data remanence

Indirect methods

- Bringing ideas and innovative thinking rather than actual solutions
- Challenge: bypass code/data protection in microcontrollers
  - detection and analysis of counterfeit products
  - compatibility purposes: develop alternative solution
  - teaching and training
- Solution
  - fault injection using power glitching
  - was used since early 90s
  - improved with bipolar glitching in late 90s
  - demonstrated on data remanence in 2018

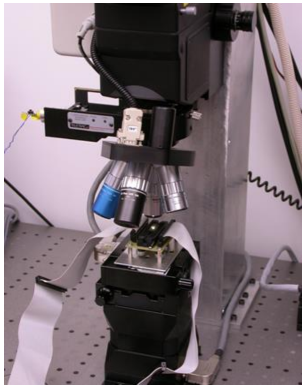
- Lesson
  - undocumented feature (or bug) in SRAM and flip-flops
  - data remanence time could be reduced by several orders of magnitude

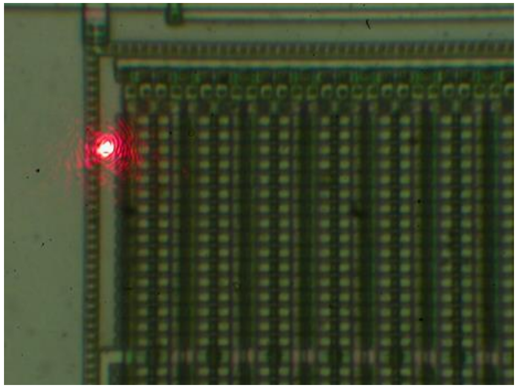
Sergei Skorobogatov: Hardware Security implications of Reliability, Remanence and Recovery in Embedded memory. PAINE workshop at Design Automation Conference (DAC-2018), 24th June 2018, San Francisco, USA. Journal of Hardware and Systems Security, 2(4), Springer 2018, pp.314-321

Indirect methods

- Challenge: disrupt normal devices operation
  - inject faults into cryptographic operations
  - take control over device operation
  - bypass security protection mechanisms
- Solution
  - optical fault injection using laser beam
  - was successfully used since early 2000s
- Lesson
  - exploiting unusual features of MOSFET transistors (light sensitivity)

Sergei Skorobogatov, Ross Anderson: Optical Fault Induction Attacks. Cryptographic Hardware and Embedded Systems Workshop (CHES-2002), 13-15 August 2002, LNCS 2523, Springer-Verlag, ISBN 3-540-00409-2, pp.2-12

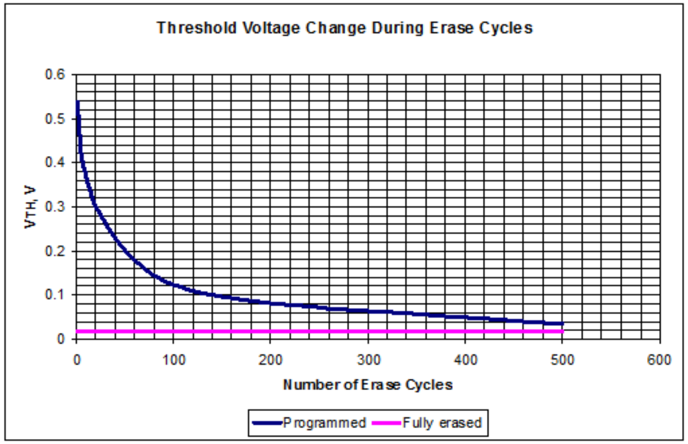


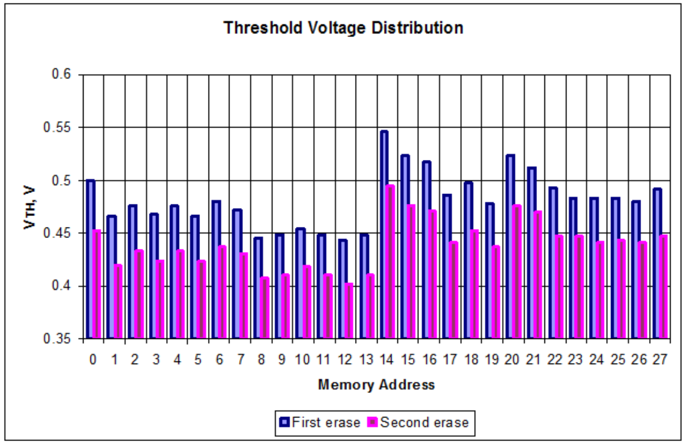


Indirect methods

- Challenge: recover data from erased memory
  - information recovery
  - forensic analysis of devices
- Solution
  - residual information present in memory cells after memory Erase operation
  - possibility of data recovery was demonstrated in 2005
- Lesson
  - undocumented features of memory transistors (incomplete erasure)

Sergei Skorobogatov: Data Remanence in Flash Memory Devices. Cryptographic Hardware and Embedded Systems Workshop (CHES-2005), 30 August - 1 September 2005, LNCS 3659, Springer, ISBN 3-540-28474-5, pp.339-353

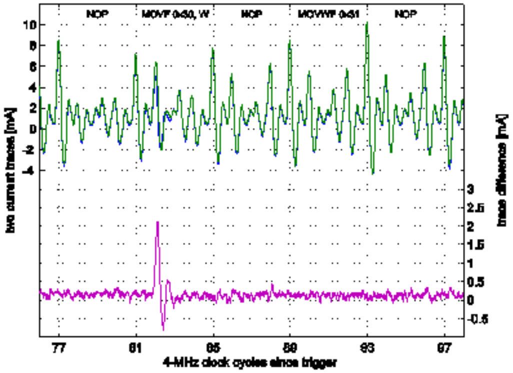




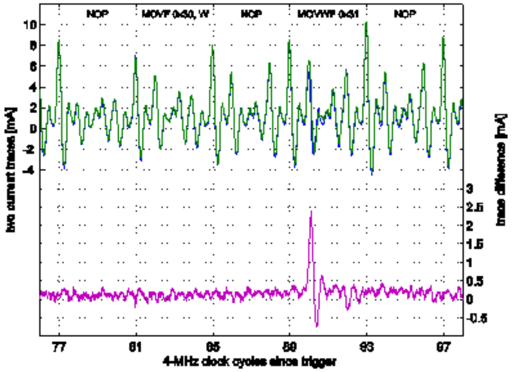
Indirect methods

- Challenge: learn about device operation and recover data
  - information recovery and partial reverse engineering
  - extraction of cryptographic keys
- Solution
  - combining optical fault injection and power analysis
  - were introduced in 2006
- Lesson
  - more powerful attacks could be created by combining several methods

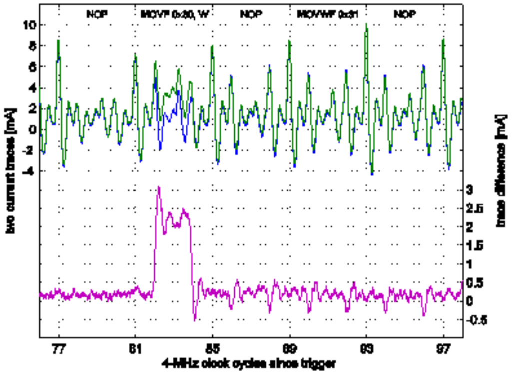
Sergei Skorobogatov: Optically Enhanced Position-Locked Power Analysis. Cryptographic Hardware and Embedded Systems Workshop (CHES-2006), 11-13 October 2006, LNCS 4249, Springer, ISBN 3-540-46559-6, pp.61-75



read memory location (laser Off/On)



write memory location (laser Off/On)

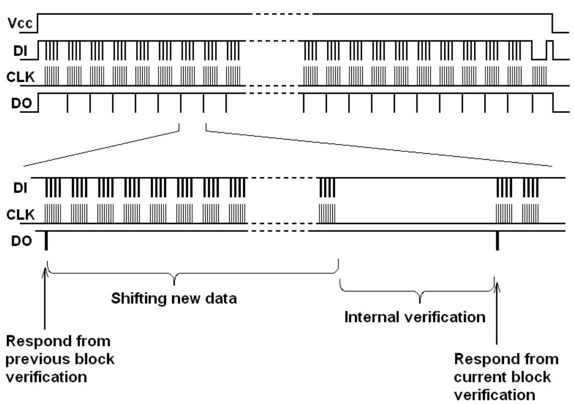


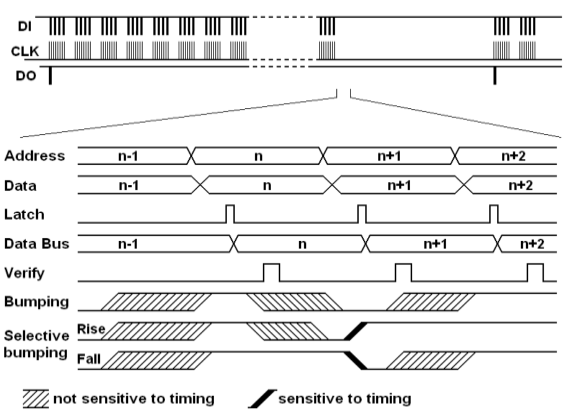
read memory location (laser Off/On)
contents of memory changed by laser

Indirect methods

- Challenge: bypass ‘no readback’ protection in devices
  - information and keys recovery
  - forensic analysis of devices
- Solution
  - memory 'Bumping attacks' as a new class of fault injection attacks aimed at the on-chip internal integrity check procedure
  - were introduced in 2010
- Lesson
  - leakage of information through a single Yes/No status

Sergei Skorobogatov: Flash Memory 'Bumping' Attacks. Cryptographic Hardware and Embedded Systems Workshop (CHES-2010), 18-20 August 2010, LNCS 6225, Springer, ISBN 3-642-15030-6, pp.158-172

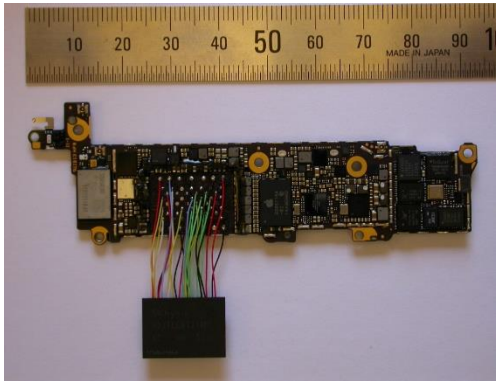


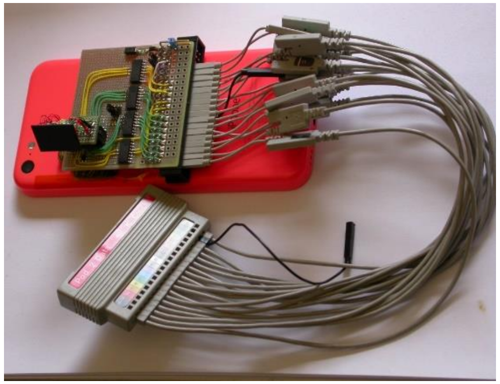


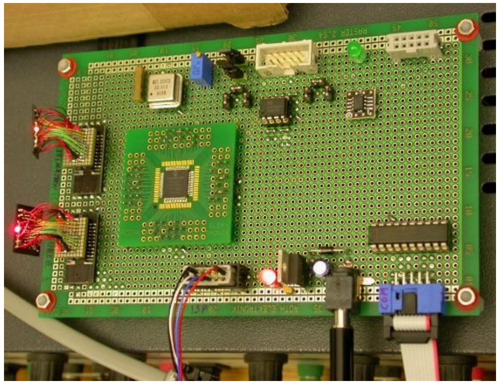
Indirect methods

- Challenge: bypass passcode protection in iPhone
  - increase the number of passcode entering attempts
  - forensic analysis of devices
- Solution
  - FBI Director claimed that making a copy of the phone’s chip to get around the passcode "doesn’t work" and aimed at "software-based“ solutions
  - NAND Mirroring attack on iPhone 5C: resetting passcode counter by rewriting Flash
  - was demonstrated in 2016
- Lesson
  - workarounds could sometime work

Sergei Skorobogatov: The bumpy road towards iPhone 5c NAND mirroring. arXiv:1609.04327, September 2016



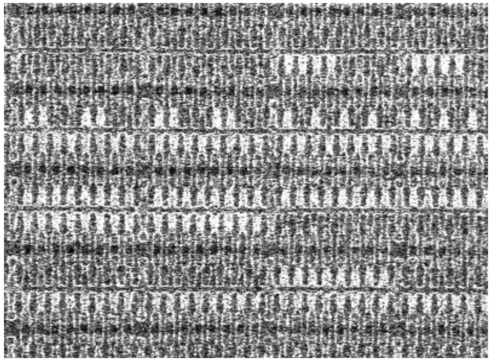


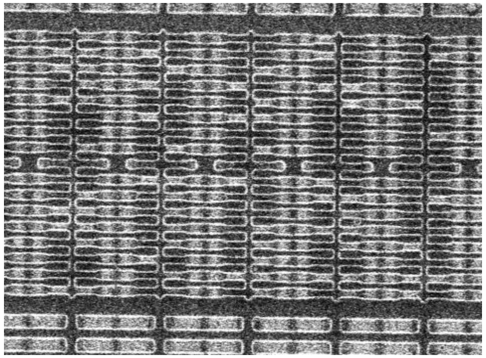


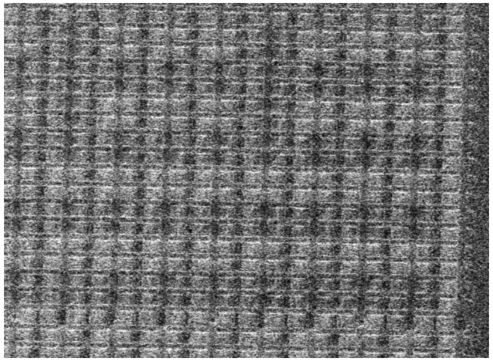
Indirect methods

- Challenge: recover data from Flash and EEPROM memory
  - information and keys recovery
  - forensic analysis of devices
- Solution
  - PVC imaging under SEM
  - more efficient and faster than Scanning Probe Microscopy (SPM)
  - was demonstrated in 2016
- Lesson
  - old techniques could be revisited for new capabilities

Franck Courbon, Sergei Skorobogatov, Christopher Woods: Direct charge measurement in Floating Gate transistors of Flash EEPROM using Scanning Electron Microscopy. In Proceedings of the 42nd International Symposium for Testing and Failure Analysis (ISTFA), Fort Worth, USA, November 2016



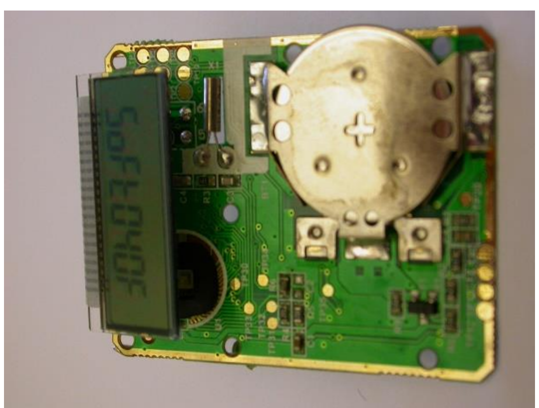


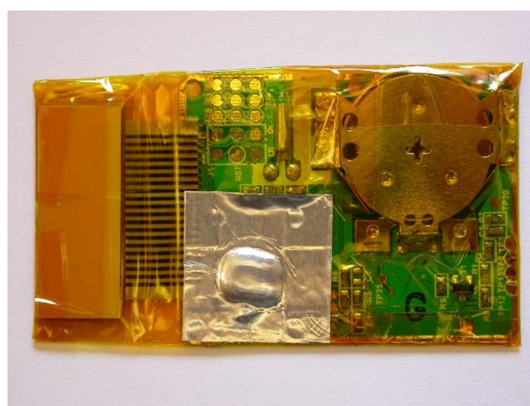


Indirect methods

- Challenge: recover data from battery backed embedded SRAM
  - information recovery
  - forensic analysis of devices
- Solution
  - decapsulation with 100% Nitric Acid
  - was demonstrated in 2018
- Lesson
  - “crazy” ideas might just work

Sergei Skorobogatov: Is Hardware Security prepared for unexpected discoveries? 25th International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA-2018), 16-19 July 2018, Singapore. IEEE Xplore 2018





Sample preparation challenges

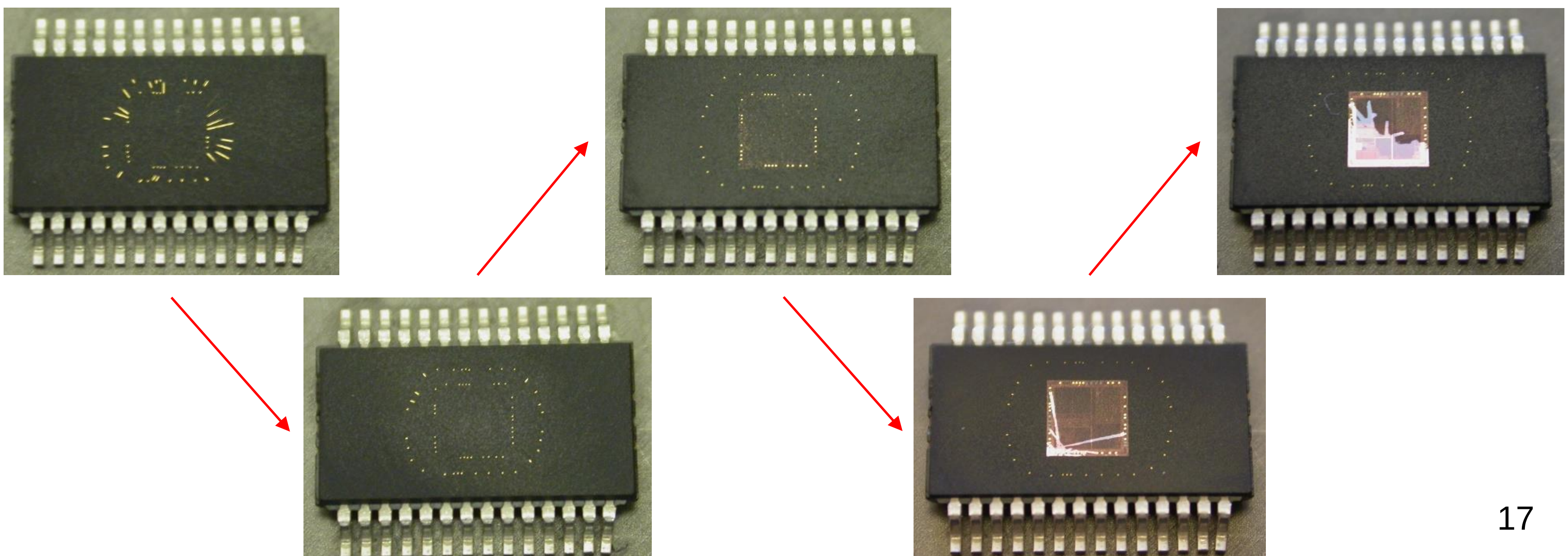
- Physical samples are essential for Hardware Security research
  - semi-invasive methods require access to die surface
- Challenges during the lockdown
  - sample preparation is sometime a messy process (chemicals, large machinery)
  - optical fault injection requires optical tables
- Some semi-invasive methods could still work
  - UV attacks only require access to the die surface, but the chip must be operational
- Partial chip decapsulation opens up the package just above the die
  - usually decapsulation starts with shallow mechanical milling to create a cavity
  - the sample is placed on a hotplate at 60˚C…70˚C under fume cupboard
  - then a drop of fuming nitric acid (>95%) is applied to the sample
  - after several seconds the sample is thoroughly washed with acetone
  - the process is repeated again from the acid step until the die is fully exposed
  - then the sample is cleaned with acetone in ultrasonic bath
  - finally the sample is dried with compressed air
  - incompatible with copper bonding wires widely used in modern ICs

Sample preparation challenges

- Is it possible to perform decapsulation without any chemicals?
  - mechanical milling with precision CNC machine
  - laser ablation followed by microwave induced plasma (MIP) etching
- Is it possible to do decapsulation without large and expensive tools?
  - suitable for home use (no dangerous chemicals, compact size)
  - affordable price
  - easy to perform
- 8-bit PIC16F1938 microcontroller was chosen as a target
  - old fabrication process (~250nm) which is sensitive to UV light
  - easy to order and fully documented
  - easy to check the results by reading Flash, EEPROM and fuses contents
- Pure mechanical approach was used
  - no chemicals involved apart from organic solvents
  - the most expensive tool is a simple polishing machine (~2k USD)
  - safe for copper bonding wires

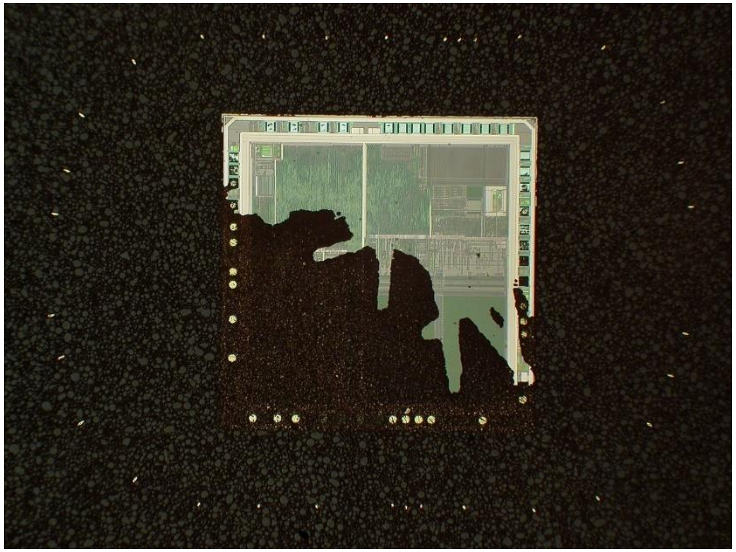
Mechanical decapsulation

- Start grinding the package from the front side of the die (package top)
  - use sandpaper with large grit (P400 or P600) until bonding wires are exposed
  - continue with medium grit sandpaper (P1000 or P1500) until the die is close
  - finish with fine sandpaper (P2500 or P4000) until the die is exposed
- What about the bonding wires?
  - they will be gone by now, but don't worry
  - bonding pads could be polished away and passivation layer scratched, but it's OK



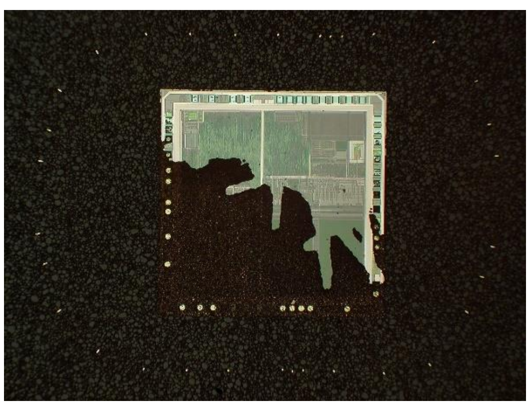
Mechanical decapsulation

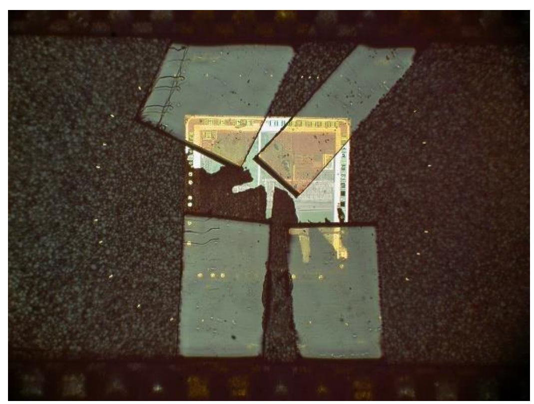
- Is it possible to restore bonding wires?
- Wire bonding machines can do the job
  - bonding pads on the die must be clean and not damaged
  - external frame must be available to which bond the wire
  - expensive and bulky machines
- What else can be used to restore the bonding wires?
  - it is not possible to solder to the remaining bits – they are too small (~20μm)
  - maybe some kind of a conductive glue can be used

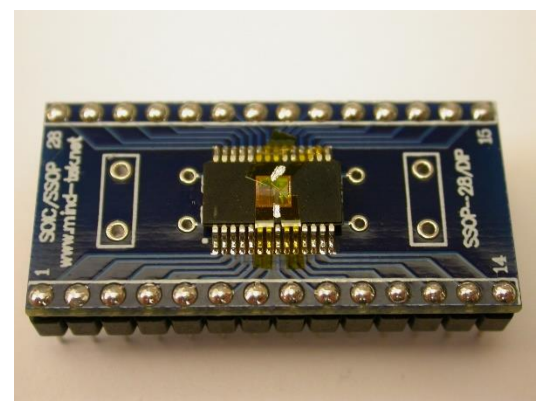


Mechanical decapsulation

- Restoring the bonding wires
  - conductive epoxy did not stick well (too low viscosity)
  - PCB trace repair paste was too thick (low viscosity)
  - conductive paint was just right
- Bonding wire restore process
  - find desired wires and bonding pads (e.g. power supply and ground pins)
  - create a template on the chip surface using masking tape
  - fill carefully the gaps with conductive paint connecting the pad with exposed wire
  - let it dry and remove the template

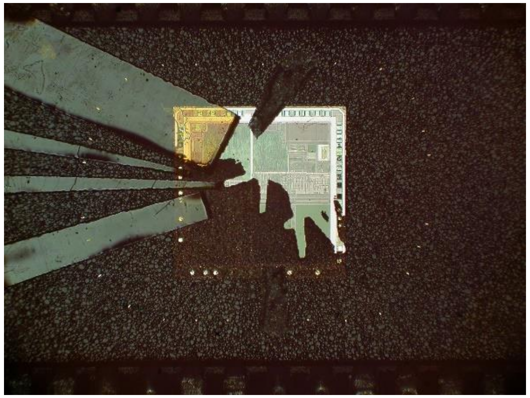
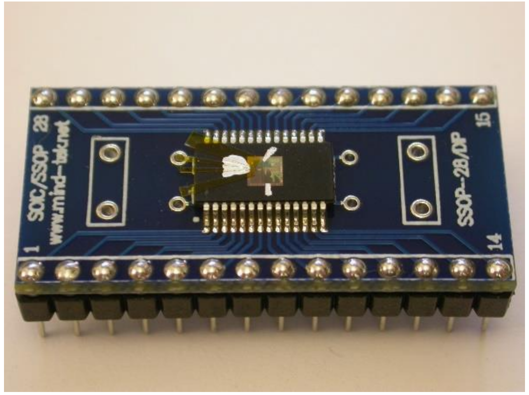
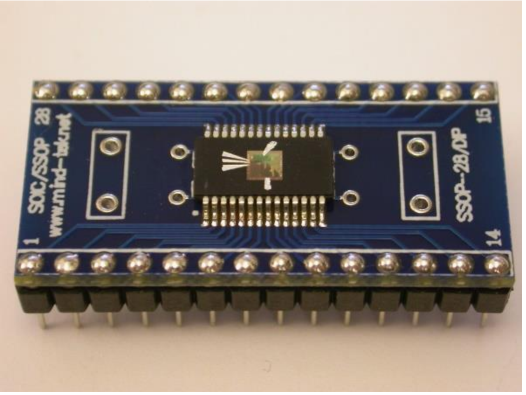






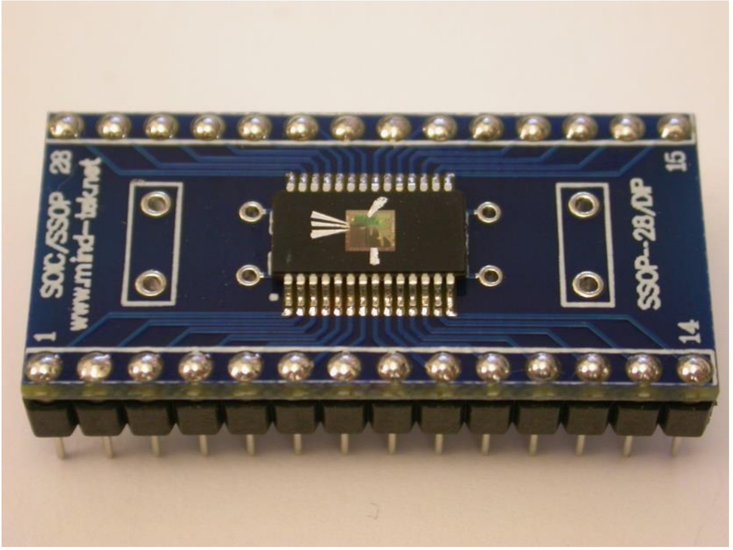
Mechanical decapsulation

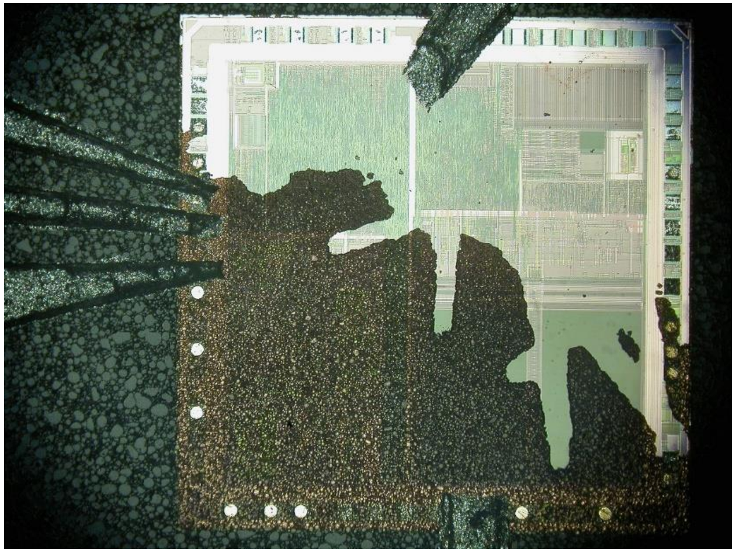
- Bonding wire restore process
  - find desired wires and bonding pads (MCLR, PGD, PGC)
  - apply new template on the chip surface using masking tape
  - fill carefully the gaps with conductive paint connecting the pad with exposed wire
  - let it dry and remove the template

Mechanical decapsulation

- Bonding wires can be restored without any dangerous chemicals
  - affordable price
  - can be safely carried out at home
  - fully functional chip despite to scratched passivation layer and polished away pads
  - robust solution
  - worked even with the die polished at a slight angle





Limitations and improvements

- Packages
  - type and material of the package: BGA/LGA are challenging
  - size of the package: small packages are particularly hard to do
  - number of pins: large number of pins result in smaller gaps
- Programming and debugging do not require many pins
  - SWI: 1 pin
  - SWD, ICSP, SMB: 2 pins
  - JTAG, SPI: 4 pins
- Mechanical stability is also important
  - can be improved with using adhesives and fillers

Future Work

- Addressing real-world problems
  - counterfeit detection: research into secure authentication devices
  - supply chain disruption: help with developing compatible solutions
- Equipment access challenges
  - develop affordable imaging solutions (aim at $100 confocal microscope)
  - develop affordable measurement solutions (aim at $100 interferometer)
  - solution: innovation, improvisation, out-of-the-box thinking and hard work
- Collaboration with industry is essential
  - bring new ideas and test new methods
  - funding is important especially if aiming to go beyond state-of-the-art
- New horizons
  - Hardware Security ← fabrication of semiconductors ← Chemistry
  - some real-world problems: energy, diseases, ecology
  - batteries ← Chemistry → capacity, charging time, safety
  - deseases → live cells ← Chemistry ← new boundaries

Conclusion

- Hardware Security relies on innovative approach and out-of-the-box thinking
- Hardware Security can help with counterfeit detection in supply chain
- Hardware Security can help in making compatible products if supply chain is disrupted
- Real world problems could be solved in innovative and out-of-the-box thinking way with some hints from Hardware Security
- Lockdown gives time to stop and look back with scrupulous analysis
- New approaches and methods are essential in fighting modern challenges and are likely to be developed
- Can Hardware Security solve more important problems?
  - probably not directly
  - but it sometime relies on Chemistry tricks to make some “impossible” things
  - Chemistry is likely to offer solutions to many challenges

Thank you!

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