The analysis of decapsulated chip surface with optical microscopy in order to detect counterfeiting

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Master's thesis
2021

Tomas Bata University in Zlín
Faculty of Applied Informatics

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Fakulta aplikované informatiky
Ústav elektroniky a měření

Akademický rok: 2020/2021

ZADÁNÍ DIPLOMOVÉ PRÁCE

(projektu, uměleckého díla, uměleckého výkonu)

Jméno a příjmení:	**Alerda Matrisi**
Osobní číslo:	**A19738**
Studijní program:	**N3902 Engineering Informatics**
Studijní obor:	**Security Technologies, Systems and Management**
Forma studia:	**Prezenční**
Téma práce:	**Analýza povrchu čipu optickou mikroskopií**
Téma práce anglicky:	**The analysis of decapsulated chip surface with optical microscopy**

Zásady pro vypracování

1.Fundamental study of counterfeit components problematics.
2.Fundamental study of semiconductor component design and technology.
3.Study of optical microscopy methodology aimed at polarization and stereomicroscopy.
4.Analyse decapsulated semiconductor chips surface with optical microscopes, study and recommend observable features suitable for authenticity evaluation.
5.Design a method for an efficient microscopy digital pictures evaluation aimed at differences between genuine and counterfeit chips.
6.Create the studied chips picture instructive set for differences demonstration.

Forma zpracování diplomové práce: **tištěná/elektronická**
Jazyk zpracování: **Angličtina**

Seznam doporučené literatury:

[1] Tehranipoor, Mark (mohammad), Guin, U., & Forte, D. (2016). Counterfeit integrated circuits: Detection and avoidance. Cham, Switzerland: Springer International Publishing.
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Datum zadání diplomové práce: **23. července 2021**
Termín odevzdání diplomové práce: **20. srpna 2021**

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ABSTRAKT

Nepůvodní elektronické součástky se staly pro jejich dnešní dodavatele podstatnou výzvou s ohledem na prevenci průniku těchto součástek do elektronických výrobků. Díky globalizaci jsou zdroje nepůvodních součástek diverzifikované a jejich zachycení obtížné. Pro účinné zvládání tohoto problému je k dispozici mnoho standardů, organizačních postupů a testovacích metod. Jedna z nejstarších a dodnes populárních metod je optická kontrola, jak pouzdra součástky, tak polovodičového systému po otevření pouzdra. Tato práce měla za cíl přispět svým dílem k této metodě. Práce je zaměřena na zdokonalení metod optické analýzy samotného systému na čipu po odstranění části materiálu pouzdra. Byly použity dva typy mikroskopů, polarizační mikroskop a stereomikroskop. Polarizační mikroskop ukázal své přednosti ve velkém zvětšení a v možnosti zpracování obrazu panoramatickým modulem. Panoramatické zpracování obrazu vychází z dílčích snímků pořízených při velkém zvětšení a jejich následným sestavením do obrazu plochy celého čipu. Stereomikroskop umožňuje pořídit ostré snímky větší struktur, jako je mikro propojení mezi čipem a vnějšími vývody, a také umožňuje zkoumání několika obvodů současně.

Klíčová slova: *nepůvodní elektronická součástka, systém na čipu, optická kontrola, polarizační mikroskop, stereomikroskop, panoramatický snímek*

ABSTRACT

Counterfeit electronic components have become a major challenge in today's supply chain. Due to globalization, the sources for these parts are highly diversified, making it increasingly difficult to capture. Several standards and testing methods are available to tackle this phenomenon. One of the most used testing methods consist on internal optical inspection where this research adds its contribution. It will provide suitable techniques to conduct internal optical inspection of decapsulated integrated circuits under a polarized and stereo microscope. The polarizing microscope showed its advantages in high magnification and in the possibility of image processing by a panoramic module. Panoramic image processing is based on partial images taken at high magnification and their subsequent assembly into an image of the area of the entire chip. The stereomicroscope allows you to take sharp images of larger structures, such as the micro-connection between the chip and external terminals, and also allows you to examine several circuits simultaneously. This information can be used during the authentication accept/reject process.

Keywords: *Counterfeit, decapsulated, integrated circuits, polarized, stereo, microscope, Panorama Modulus, authentication*

ACKNOWLEDGEMENTS

Working on a thesis in the midst of a pandemic has had its perks. This wouldn’t have even been possible if it wasn’t for my advisor **Ing. Petr Neumann, Ph.D.** His willingness, knowledge, encouragement and positive approach on every issue that came my way, has made this journey very pleasant. I will be forever grateful not only for his academic help, but also his mental and spiritual support.

My completion of this thesis wouldn’t have been accomplished without the guidance and feedback of **Ing. Milan Navrátil, Ph.D.** Always willing to help and be there for me regardless of his working hours or circumstances. His knowledge and precision were extremely helpful and made this work feasible.

I would also like to express my gratitude to the whole academic body of the Faculty of Applied Informatics. **doc. Ing. Jiří Vojtěšek, Ph.D.** for always being the source of information regarding any point in my academic progress. **doc. Ing. Marek Kubalčík, Ph.D.** for his prompt and efficient response to all times.

Finally, my deep and sincere gratitude to my family and for their continuous and unconditional love, help and support. I will always be grateful to my parents; they gave me opportunities and experiences that made me who I am today. They selflessly encouraged me to explore new directions in life and find my own destiny. Without them, this journey would be impossible and I dedicate this milestone to them. Not to forget my friends Ami, Gili, Rafi who gave me happy distractions and lots of laughs.

I hereby declare that the print version of my Bachelor's/Master's thesis and the electronic version of my thesis deposited in the IS/STAG system are identical.

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INTRODUCTION

In recent years, as the demand for cost reduction has increased, counterfeit components have been defined as a problem that has received increasing attention. Counterfeit products refer to any item that is intended to mislead its buyers or users. Misrepresentation is usually due to known defects or other performance deficiencies. Regardless of their use, be it, medical, military [6] or commercial applications, a counterfeit component can cause fatal failure at a critical time. According to IEEE Spectrum, authorized electronics companies suffer a loss of approximate $100 billion of global revenue every year because of counterfeiting [5]. The counterfeit "industry" has progressed from a small inferior workshop into a well-coordinated production process [3]. In return, this also requires for more sophisticated methods to detect counterfeit electronic parts entering the market.

Hence, this research through the interior optical inspection of decapsulated chips aims to tackle the issue. Polarized and Stereo microscopes make it possible to capture high-quality images that can be late on used for counterfeit detection purposes.

RESEARCH QUESTION: How can polarized and stereo microscopy be used to retrieve high quality digital images aiming to detect counterfeiting? Experimenting on different techniques that the internal optical inspection offers, we intent to conclude on a suitable method on capturing high quality digital images.

This research will be split into two main parts: "Theory" and "Analysis". In Theory section an overview of multiple previous researches conducted up to now will be presented. An introduction to the topics and the current main methods being used during inspection process, taxonomy and main defects of IC will be included. It will be followed by the Methodology section where the experimenting done with the polarizing (ZEISS Axio Scope.A1) and stereo (Stemi 2000-C) will be presented and illustrated in detail. The Results section will contain the images obtained from the methodology implemented. Lastly, the conclusions section will summarize the findings and give recommendations for future possible researches.

1 COUNTERFEITED GOODS

According to Cambridge Dictionary "Counterfeit" means to "made to look like the original of something, usually for dishonest or illegal purposes". It covers a wide scope of consumer goods, from complete fakes, non-functional lookalikes (such as drugs and medications), functional but less important items (such as empty videotapes), to fully functional items illegally produced without giving copyright fees (music from CDs or movies on DVDs) [1]. Recently the counterfeit products have become way harder to differentiate from genuine pieces. The counterfeit "industry" has progressed from a small inferior workshop into a well-coordinated production process [3].

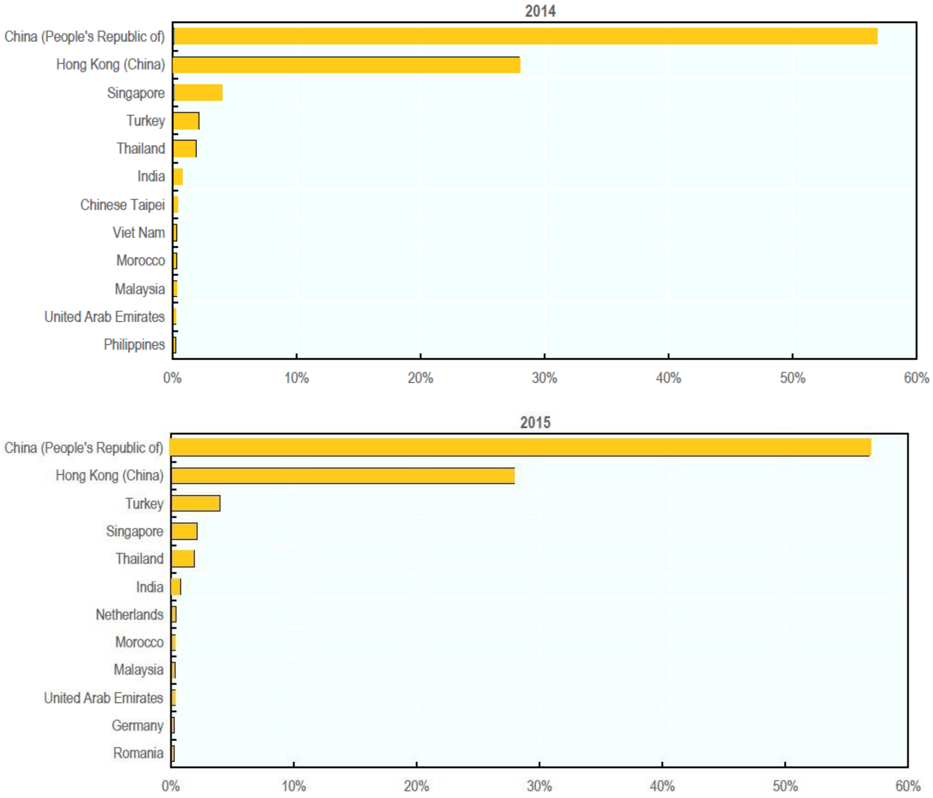
Globalization has increased the risks and possibilities for crime organizations to free ride on others' intellectual assets and pollute trade routes with counterfeits. These goods, once they find their way into the market pose a big threat to the economy, health, and safety of the consumers. On the other hand, the trade of forged items creates profit for crime organizations at the expense of companies and governments [2]. Billions of dollars go into the research, development and manufacturing of new products. Additional costs may come from the ongoing support for released products. Counterfeiters are exempt from most of these costs. They are able to reap the benefits from innovation created by others, which in result, takes away resources from future innovation of products. Practitioners of counterfeiting are not liable for the poor quality of their products either. In the event of damage caused by a faulty component, the blame is shifted to the original manufacturer [3]. According to a study conducted by Organization for Economic Cooperation and Development OECD and the EU's Intellectual Property Office, the trade in counterfeit and pirated goods has increased steadily in the last few years and now stands at 3.3% of global trade [2].

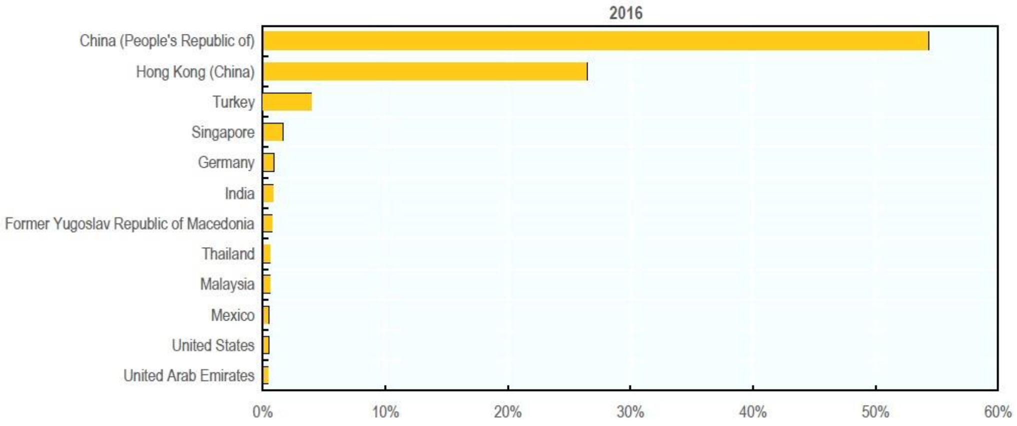
Even though electronics products are highly sophisticated in design and their manufacturing process is complex, counterfeiting still finds its way. In a study done by Alliance for Gray Market and Counterfeit Abatement (AGMA), one in ten information technology products sold may be counterfeit, as reported by interviews conducted with electronics industry executives. It is estimated that about US$100 billion of global IT industry revenue is lost to counterfeiters each year [4]. Counterfeit electronics have found their way in every industrial sector, including computers, telecommunications, automotive electronics, avionics, and even military systems [5]. An investigation done by the Senate Armed Services Committee in the

U.S.A uncovered a large number of counterfeit parts that were detected in the critical defense system. One of the many conclusions that this report came to, was that almost 70 percent of the suspect parts traced to China [6].

The People's Republic of China remains the main source for producing counterfeit goods [3]. Lately, many other countries in Asia including India, Malaysia, Pakistan, Thailand, Turkey, and Vietnam are producing these goods, yet again their role is not as significant as China's [2]. China and Hong-Kong (China) have been dominating global trade in counterfeit goods during the 2014-2016 period (Figure 1.) and as well as during 2011-2013. It is important to point out however, that Hong-Kong's (China) share has been increasing progressively meanwhile China's has been decreasing [2]. The graphics illustrated below give a clearer picture.

Figure 1 *Seizures of counterfeit and pirated goods: Top provenance economies, 2014 -15-16*

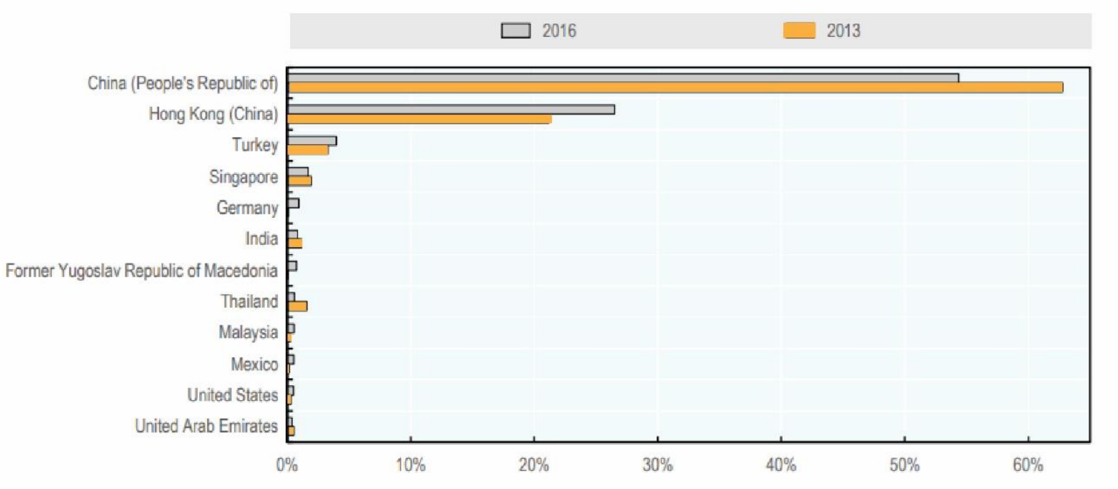




Note: Adapted from:" OECD/EUIPO (2019), Trends in Trade in Counterfeit and Pirated Goods, Illicit Trade, OECD Publishing, Paris, https://doi.org/10.1787/g2g9f533-en.

Turkey, Singapore, India, Malaysia, Mexico, Thailand, and the United Arab Emirates continued to be the world's largest source economies for counterfeit and pirated product transactions in 2013 and 2016 (Figure 2.). [2]

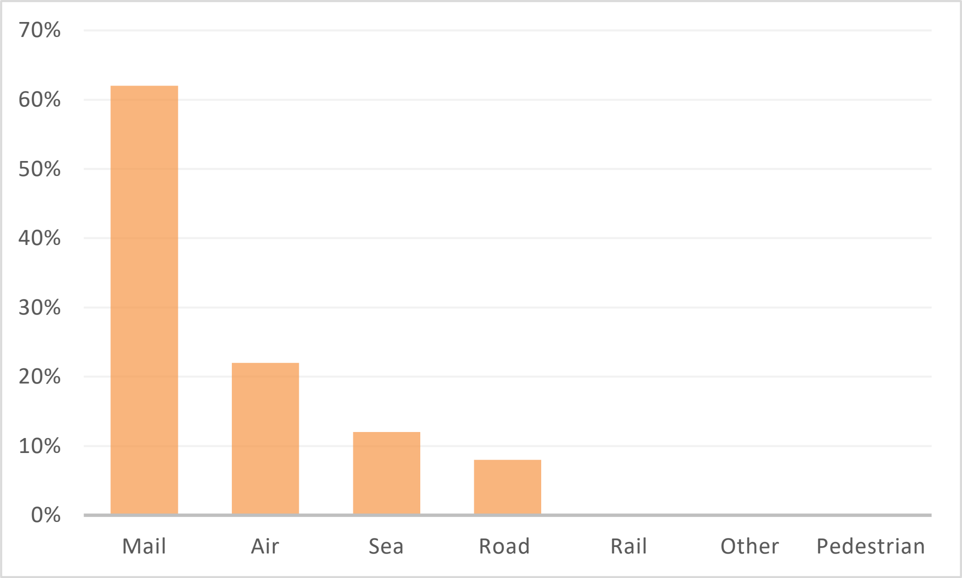
Figure 2 *The % of IP-infringing items seized by customs throughout the world*



Note: Adapted from:" OECD/EUIPO (2019), Trends in Trade in Counterfeit and Pirated Goods, Illicit Trade, OECD Publishing, Paris, https://doi.org/10.1787/g2g9f533-en.

Later on, finding the routes these products take to get into the market is very complicated. Groups that are part of this trade usually transport fake products through complex routes, by circulating the products through networks of multiple locations before reaching their destination [2]. Another means of transport that is gaining much popularity is through postal shipments. As we can see in (Figure 3.) mail accounted for 62 percent of worldwide seizures were postal shipments.

Figure 3 *Conveyance methods (2011-2013)*



Note: Adapted from:" OECD/EUIPO (2019), Trends in Trade in Counterfeit and Pirated Goods, Illicit Trade, OECD Publishing, Paris, https://doi.org/10.1787/g2g9f533-en.

The fast development of e-commerce has given counterfeiters a powerful platform to easily obtain a big number of customers. In March 2021 Apple Inc. conducted a study [7] on counterfeit market exchange for Apple products on Instagram. The research focused on specific products like chargers, headphones, and power cables. Instagram was flooded with counterfeit products and the majority of these vendors appear to come from China. Another point made was related to the fact that these sellers made a fortune sometimes reaching up to $ 140,000 in a single day of online sales.

The companies affected by counterfeiting and piracy are mainly located in the United States, France, Switzerland, Italy, Germany, Japan, Korea, and the United Kingdom [2].

Among all these products that are being forged, electronics remains to be one of the biggest categories where components including integrated circuits (ICs), printed circuit boards

(PCBs), and different types of discrete components are excessively counterfeited [3]. According to data provided by IHS, the five most commonly counterfeited semiconductor types are analog integrated circuits (ICs), microprocessors, memory ICs, programmable logic devices, and transistors, all of which are commonly used in commercial and military applications. IHS stated that these five commodity categories combined accounted for a little more than two-thirds of all counterfeiting incidents reported in 2011. [11]

Table 1 Incidents per IC 2011

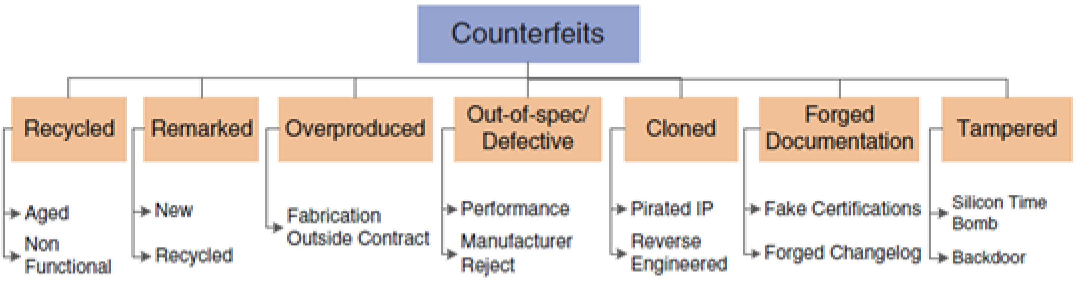
Rank	**Type**	**% of Reported Incidents**
1	Analog IC	25.3%
2	Microprocessor IC	13.4%
3	Memory IC	13.1%
4	Programable Logic IC	8.3%
5	Transistor	7.6%

Note: Adapted by: McGrath, D. (2012, April 04). IHS: Counterfeit parts represent $169B annual risk. Retrieved from *https://www.eetimes.com/ihs-counterfeit-parts-represent-169b-annual-risk/*

1.1 Types of Counterfeit Integrated Circuits

Giving an explicit definition of what can be considered a counterfeit Integrated Circuit can be difficult. As there could be many possibilities that don’t fall under that specific frame. Recently a broader and more comprehensive taxonomy of counterfeit types has been made [3]. We classify the counterfeit types into seven distinct categories shown in Figure 4.

Figure 4 *Counterfeit Types*



Note: Source: M. Tehranipoor et al., Counterfeit Integrated Circuits, DOI 10.1007/978-3-319-11824-6_1

1.1.1 Recycled:

“Recycled” is considered an electronics component that is taken from a system and later on changed to resemble a new part. Recycled and remarked counterfeit types are the most argued types out of all the rest. It is stated that more than 80% of forged components are recycled and remarked in the supply chain today. In Figure 5. the recycling process is illustrated.

A recycling process has the following steps:

I. The first step consists of collecting discarded printed circuit boards (PCBs). Out of these boards, different components such as (ICs, capacitors, transistors, etc.) are acquired.

II. On top of an oven flame the PCBs are heated for the soldering material to melt down so the component can start detaching. The board is smashed into a bucket and collects the parts.

III. Components have an original marking set by the original manufacturer. These markings are erased using micro blasting machines. The machine hits the surface of the component with agents by using compressed air to accelerate the process. Agents are usually aluminum oxide powder, sodium bicarbonate powder, and glass beads. The agents used depend on the type of component that is being used on.

IV. At this point the surface has been worn out a bit so it needs a new coating layer. A blacktopping resurfacing material is applied to the component.

V. Now there’s a blank surface to print the new markings on. These markings contain information like date codes, manufacturers logo, and location, PIN numbers etc. Using an ink or laser printer all this information is transferred on the surface.

VI. In the end, the finishing touches are given to make the components look like new ones. Some parts such as leads, columns, or soldering balls get refined. Leads are straightened and replanted with new materials [3].

Figure 5 *Recycling Process*

Note Source: OECD/EUIPO (2019), Trends in Trade in Counterfeit and Pirated Goods, Illicit Trade, OECD Publishing, Paris, https://doi.org/10.1787/g2g9f533-en.

1.2.2 Remarked:

In remarked counterfeits, the surface of the component is sanded in order to remove the original marking for it to be remarked again with forged information. The marking usually consists of part numbers, country of origin, logos, etc. After the sanding or grinding part, a new coat is put on the component with new information. This practice is used to give components a better rate (e.g., from a simple commercial level to an industrial one). Other reasons consist of updating date codes with more recent ones or remarking parts that have not passed manufacturing control tests [10].

Figure 6 *Heated Solvent test reveals blacktopping*

Zambito, M. (2018). How to Spot a Counterfeit: Heated Solvent Testing. Retrieved from https://actestlab.com/wp-content/uploads/2018/07/ERAI_HowSpotCfeit-HSTbyACT_Q22018.pdf

1.1.2 Overproduced:

The manufacturing process of integrated circuits has gone through changes since the complexity and the cost of these parts is increased. These design houses have outsourced their designs and products to factories all around the world. Companies agree to produce a certain number of pieces, but that doesn't stop them from exceeding it. Some contractors may produce a bigger number of pieces and hide the actual percentage of defect-free components. They can easily sell these pieces on the market and gain profit. Unfortunately, this is a loss for the design house, and they overproduce to meet the required numbers. Since these outscored parties are far from the main company it's hard for the production process to be monitored. Besides the fact that the design houses spend a lot of resources on the design and production of these pieces, another thing to point out is their reliability. Minimal or even no testing is done to these components holding the original manufacturer's name [10].

1.1.3 Out-of-Spec/Defective:

During the manufacturing production process multiple tests are conducted on components. If these components fail to meet the required levels, they are considered out of specifications or rejected. They are supposedly destroyed and properly disposed of, but they can easily be stolen and sold on the open market without the awareness of the main facility. If these parts find their way to the supply chain it will be very hard to detect them as counterfeit, especially if the component failed the later test phase. The tester should have very specific knowledge of the inner structure of the component in order to conclude. Unfortunately, this is not usually the case and these parts continue to pose a big threat to the system [10].

1.1.4 Cloned:

Cloning is considered the act of copying a design from a company in order to reduce the costs of research and development. There are two ways to achieve it. First through reverse engineering. In this case, designs are copied, and they produce the exact copy of the original version. Another way is through taking the information from a person who has close knowledge of the design. Usually, chips have design constraints and power signatures. If these assets are weak or not put yet, they can easily get cloned and marked to profit [10].

1.1.5 Forged Documentation:

When shipped any components sold are accompanied by a document containing its specifications, testing, certificates of conformance (CoC), and statement of work (SoW). This information can be modified or forged, and the component can be mistaken and sold as a non-defective part. Detecting these parts is hard because some old designs may not be included on the Original Component Manufacturer (OMC). This makes the authenticity process a very complicated one [10].

1.1.6 Tampered:

Tampering with a part can occur at any point in its life cycle. It may be at the die level (“hardware Trojan”) or at the package level. Such components may either function as a silicon time bomb, causing the computer to behave differently in certain circumstances, or as a backdoor, allowing hidden data from the chip to be sent to an adversary. A piece of hardware Trojan has the ability to change the functionality of a design in a number of ways. A hardware Trojan may, for example, disable a design's crypto module and reveal unencrypted plain text that can be easily captured or disable a module's device clock for a short period of time to initiate sabotage [9]. Since the chip behaves not as it's supposed to, we can count them as counterfeit.

2 COUNTERFEIT DEFECTS

For detecting counterfeit components, a wide range of test methods is currently available. The aim of these techniques is to find "defects" in a component or a batch of parts that are being investigated. Anomalies and changes not usually present in genuine parts are referred to as counterfeit defects. A counterfeit part is likely to have one or more defects and/or discrepancies from the legitimate component's normal/usual shape and/or features. Functional (i.e., connected to the leads, bundle, etc.) or electrical disturbances may be present (e.g., degradation in its performance or a change in its specifications) [3].

We shouldn't find any flaws in legitimate parts and we believe that foundries and assemblies use a reasonably standardized production procedure and thoroughly inspect their components. As a result, all anomalies or faulty behaviors in a part must be traced to counterfeiting.

2.1 Physical defects

The physical properties of the parts are closely related to physical defects. Depending on where the flaws in the packaging are located, they may be labeled as external or interior defects. Packaging/shipping, leads/balls/columns, and the box of a part are examples of exterior defects. The most noticeable flaws would be those related to the manufacturing or shipment with which the pieces came. If an IC has been used before, the leads/balls/columns will reveal how the component was treated. They should be physically consistent with the datasheet's requirements, including size and shape. An IC's packaging will provide a lot of information about the chip. Since this is where the product numbers, country of origin, date codes, and other things are marked, counterfeiters can aim to avoid damaging something to make the box appear as genuine as possible. Bond wire and die-related defects are the two most common forms of interior defects. Bond wire faults include missing/broken bond wires within the box, a weak connection between the die and the bond wire, and so on. The die shows a large amount of useful info about the part. Die scratches, defects, and other die-related defects are examples [3].

2.2 Electrical Defects

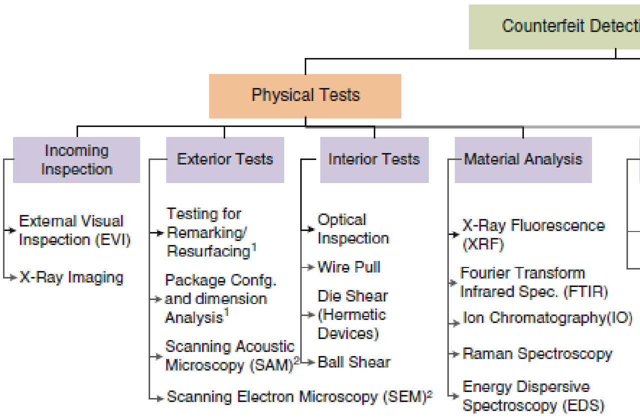
Typical electrical defects can be divided into two categories: parametric defects and manufacturing defects. Parametric defects consist of alterations in component parameters caused by previous usage or temperature. An alternation of parameters can be aging, caused by it being used for a certain amount of time [10].

Manufacturing defects happen during the fabrication process of components and are divided into three categories – process, material, and package. The defects in the process group are caused by the fabrication methods of photolithography and etching. Impurities in the silicon and oxide layers cause the defects related to the materials. The die is protected by the passivation layer, but corrosion creates cracks or pin holes, which leads to failure. The presence of sodium and chloride will quickly contaminate the aluminum oxide layer, resulting in a visible defect [10].

3 COUNTERFEIT DETECTION METHODS

Manufacturers, dealers, and consumers of electronic components must now inspect all incoming electronic components for authenticity, especially parts obtained from non-OCM-authorized distributors. It is important to investigate new counterfeit identification methods in order to inspect them.

Figure 7 *Counterfeit Detection Methods*



Note Source: OECD/EUIPO (2019), Trends in Trade in Counterfeit and Pirated Goods, Illicit Trade, OECD Publishing, Paris, https://doi.org/10.1787/g2g9f533-en

3.1 Physical Inspection

In order to detect physical defects of counterfeited parts a physical inspection is performed. It is used to examine the physical and chemical properties of the package, die and leads of the component [10].

3.1.1 Incoming Inspection

When an order is brought in, it goes into the incoming inspection process first. All the components under test go thorough necessary inspections and tests to ensure their conformance to the requirements [12]. In low power visual inspection, all the components are strictly documented and inspected. Low power visual inspection requires a low power microscope (generally less than 10X magnification) to inspect the exterior side. The markings on genuine components tend to be clear and identical. The internal structure of the component being tested is analyzed using X-Ray imaging. If a known good component (golden model) is available, one can compare the images taken from the tested piece with this golden model [3].

3.1.2 Exterior Test

The outer part of the package and leads of the components being tested are being analyzed by using exterior tests. Hand-held or automatic measurement equipment is used to calculate the actual measurements of the parts being tested. Each calculation that differs significantly from the specification sheet means that the part is likely counterfeit. Micro blasting analysis is a dry and excellent blasting method. Multiple blasting agents with appropriate grain sizes are bombarded on the surface (package) of the component, and the materials are gathered for analysis. Some popular blasting agents are aluminum oxide powder, glass beads, sodium bicarbonate powder etc. Hermeticity testing is a form of package inspection that examines the hermetic seal of hermetically sealed parts. The seal on such components ensures that they operate correctly in the condition for which they were made. In case the seal gets broken or damaged, the component gets defected [10].

Scanning acoustic microscopy (SAM) is one of the most effective, but costly, methods of studying a component's structure. This technology generates a representation of the component based on its acoustic impedance at varying depths by using the reflection or propagation of ultrasound waves. This is extremely helpful in the analysis of delamination [9]. The arrangement of bond wires, as well as cracks and voids in the die, can be detectable.

3.1.3 Interior Test

Delidding/decapsulation is used to check the internal structure, die, and bond wires of the components being examined. Decapsulation can be achieved using one of three main commercial procedures. These are chemical, mechanical, or laser-based tools. The chemical decapsulation etching away of the package is done with an acid solution. More recent laser-based techniques can remove an area of the package. Mechanical decapsulation consists of grinding the surface until the die is uncovered. Once the component has been decapsulated and the required parts have been revealed, other steps will follow [10].

In optical inspection, all the relevant information related to die and bond wires are properly documented. The information like die markings (company logo, date code, chip ID, country of manufacturer, etc.), bond wire positions, bond types, etc. are to be documented. The integrity of the bonds with the die is tested using wire pull. The adhesiveness between die and bond wires deteriorates in time if the component has been utilized. By comparing the tension (pulling force) of the component being tested with the golden version, we can detect if the piece has been previously used. We are able to control the die attach integrity in hermetic devices. A ball shear test is conducted to check the ball bond integrity at the die [3].

The images of a die, package, or lead are captured using scanning electron microscopy (SEM), which uses a directed beam of electrons to scan it. It can quickly be observed by SEM if there is a defect in it. It has an efficient resolution of a few nanometers, implying that it can evaluate the die down to the gate stage. This is helpful for a detailed examination of the die [10].

3.1.4 Material Analysis

The chemical composition of the component tested is verified using material analysis. Defects such as incorrect materials, contamination and oxidation of leads and packages, etc., can be analyzed and detected. The following are a few of the more well-known tests: X-Ray fluorescence (XRF), Fourier transform infrared spectroscopy (FTIR), ion chromatography (IO), Raman spectroscopy, and energy dispersive X-ray spectroscopy (EDS) [3].

3.2 Electrical Inspections

Electrical tests require different test set ups for all the unique types of ICs one could encounter in practice (digital, analog, mixed signal, memories, processors etc.). Below we will explain the electrical tests currently available.

3.2.1 Parametric Tests:

If the chip is used before, the DC and AC parameters may shift from its specified value (mentioned on the datasheet). After observing test results from a parametric test, a decision can be made as to whether or not a component is counterfeit. In *DC parametric tests*, the parametric measurement unit (PMU) of an automatic test equipment forces an I/O voltage and current to a steady state and measures the electrical parameters using Ohm’s law. The DC parametric tests can be classified in different categories - contact test, power consumption test, output short current test, output drive current test, threshold test, etc. In *AC para-*

metric tests, the measurement of AC parameters (terminal impedance, timing, etc.) is performed by using AC voltages with a set of frequencies. AC parametric tests can be classified as follows: rise and fall time tests, set-up, hold and release time tests, propagation delay tests, etc. DC parametric tests include voltage bump test, leakage tests, etc. AC parametric tests are classified as set-up time sensitivity test, access time test, running time test, etc. [10]

3.2.2 Functional Tests:

Functional tests are the most efficient way of verifying the functionality of a component. Any defects that impact the functionality (e.g., from some easy defects – missing or broken bond wires, missing or wrong dies, etc., too hard to detect defects related to process, material and package) can be detected. In *function verification*, the functionality of a component is verified. It determines whether individual components, possibly designed with different technologies, function as a system and produce the expected response. In *memory tests*, read/write operations are performed on a memory to verify its functionality. [10]

3.2.3 Burn-In Test:

In burn-in, the device is operated at an elevated temperature to simulate a stress condition to find infant mortality failures and unexpected failures to assure reliability. The implementation of burn-in is very important as it can easily weed out the commercial grade components marked as military grade. It can also remove defective components or those components that were not designed to perform under these stress conditions [10].

3.2.4 Structural Tests:

Structural tests are very effective in detecting manufacturing defects for out-of-spec/defective counterfeit types. It can detect the cloned (reversed engineered) counterfeit components if there are some anomalies in the reverse engineering process. If the cloned netlist does not match with the genuine netlist even if for a few gates, some of the structural test vectors will produce an incorrect response and the component being tested will be flagged as defective. It can also detect some of the delay defects due to aging in recycled and remarked counterfeit types [3].

3.3 Review of detection methods

As previously described, counterfeit detection of electronic parts can be separated into two main categories: physical inspection and electrical testing. The physical inspection techniques examine the IC or component package exterior and interior, which provide everything from basic visual inspection to high-tech imaging solutions that require X-ray, Infrared, transmission electron microscopy (TEMs), focused ion beams (FIBs), etc. [14]. On the other hand, electrical tests capture chip curve trace, contact degradation, device parameter distributions, etc. and compare them to the device specifications [15]. The physical approach can be applied to all component types. However, some of the methods like the interior ones are destructive and take hours to run. Therefore, such tests are done on a sample of components. On the other hand, electrical methods are nondestructive and time efficient compared to physical tests. No sampling is required, and all the parts can be tested. However, electrical tests do not target all types of components in the same way or uniformly, e.g., the test sets for functional verification of an analog chip are completely different than its digital counterpart [16]. Both approaches come with their own challenges that we will present in the upcoming section.

3.3.1 Physical Inspections:

Physical methods generally focused the inspection of the physical structure and the material analysis of a component. The major challenges for the implementation of physical inspections are:

(i) Sampling: Most of the physical tests are destructive. Sample preparation is extremely important as it directly relates to test confidence. If a few counterfeit components are mixed with a large batch, the probability of selecting the counterfeit one for test is extremely small.

(ii) Test Time and Cost: The test time and cost are major limiting factors in the use of physical tests for counterfeit detection. The equipment used for physical inspections (e.g., scanning electron and acoustic microscopy [SEM or SAM]) are not custom-designed to detect counterfeit parts. It takes several hours (e.g., typically more than 8 hours for SEM analysis) to test a single component with good resolution.

(iii) Automation: These tests are done when needed with no metrics for quantifying against a set of counterfeit types, anomalies, and defects. Most of the tests are carried out without automation.

(iv) Metrics: Currently, there are no metrics to evaluate the effectiveness of physical inspections. The test results mostly depend on the subject matter experts (SMEs). The decision-making process is entirely dependent on the operator (or SMEs) – this is indeed error prone. A chip could be considered counterfeit in one lab while it could be marked as authentic in another lab. [16]

3.3.2 Electrical Inspections:

Electrical tests have the potential to be an efficient means of counterfeit detection, as they do not have the limitations of physical inspections. However, there are major challenges that are unique to electrical tests.

In this section, we will briefly discuss the limitations of the electrical:

Parametric tests are generally very time efficient. However, due to increased process variations and environmental variations (temperature, noise, aging, etc.), the electrical parameters of a component vary significantly. It will be very difficult to conclude whether the variations in the parameters of a component are due to the aging (for recycled and remarked components) or to the process variations in the circuit [17].

One can perform a statistical analysis based on the data observed from the parametric tests to determine the confidence level that a part is counterfeit with or without a golden IC. The efficiency of such analysis must be proven on a large number of golden and counterfeit parts. The requirement of having a high-speed tester in order to apply functional test patterns to chips make it extremely expensive. It is nearly impossible to get the complete set of test vectors for an obsolete part from the OCM. In some cases, the OCM may no longer exist or the information required may no longer be available in archived records at the OCM. Burn-in tests are useful in detecting infant mortality failures of components. However, because of excessive test time and cost, these tests are only attractive and useful only for critical and high-risk applications. The implementation of structural tests in counterfeit detection is extremely challenging for several reasons. First, the structural tests require total access to the internal scan chains of a component. Sometimes, IP owners do not give permission to access their design and disable the internal scan chains with a fuse. Second, obsolete parts may not have design for testability (DFT) structures implemented. Finally, analog chips cannot be tested.

4 POLARIZED AND STEREO MICROSCOPY

In this chapter, Polarized and Stereo Microscopy will be presented. Since these techniques will be used during the analysis of decapsulated chips it is important to have an overview of how the microscope works and the science behind it. This chapter aims to present the different characteristics of both methods and not to compare them.

4.1 Polarized Light Microscopy History

The history of light polarization begins with Erasmus Bartholinus (1625-1698), a Danish physicist, physician, and mathematician [13] who discovered the phenomena of double refraction of calc-spar (or Iceland spar, a type of calcite) in 1669, while not being aware of the phenomenon of polarization. Later, Christian Huygens (1629-1695), a Dutch physicist and astronomer, explained double refraction by supposing that, in addition to a main spherical wave, a secondary ellipsoidal wave exists in the crystal. Huygens discovered the basic finding of polarization in 1690 while working on this project: each of the two beams emerging from calcit refraction may be extinguished by passing it through a second crystal of the same material that is rotated around the ray's direction. The polarization of light through reflection was discovered by Étienne Louis Malus (1775-1812), a French engineer: He examined the reflection of direct sunlight from a window glass through a calcit crystal in 1808, and discovered that the relative strengths of the two images generated by double refraction changed as the crystal was rotated about the line of sight. Malus, on the other hand, made no attempt to explain this occurrence. For linearly polarized incident light, he developed the Malus law, which states that the intensity of light transmitted by a polarizer is proportional to the square of the cosine of the angle of direction of the transmission axis.In reality, it was Malus who originated the term "polarization" to describe light. He theorized that following reflection, the light corpuscles were aligned in the same way as magnetic bodies are aligned by the poles of a magnet. [20]

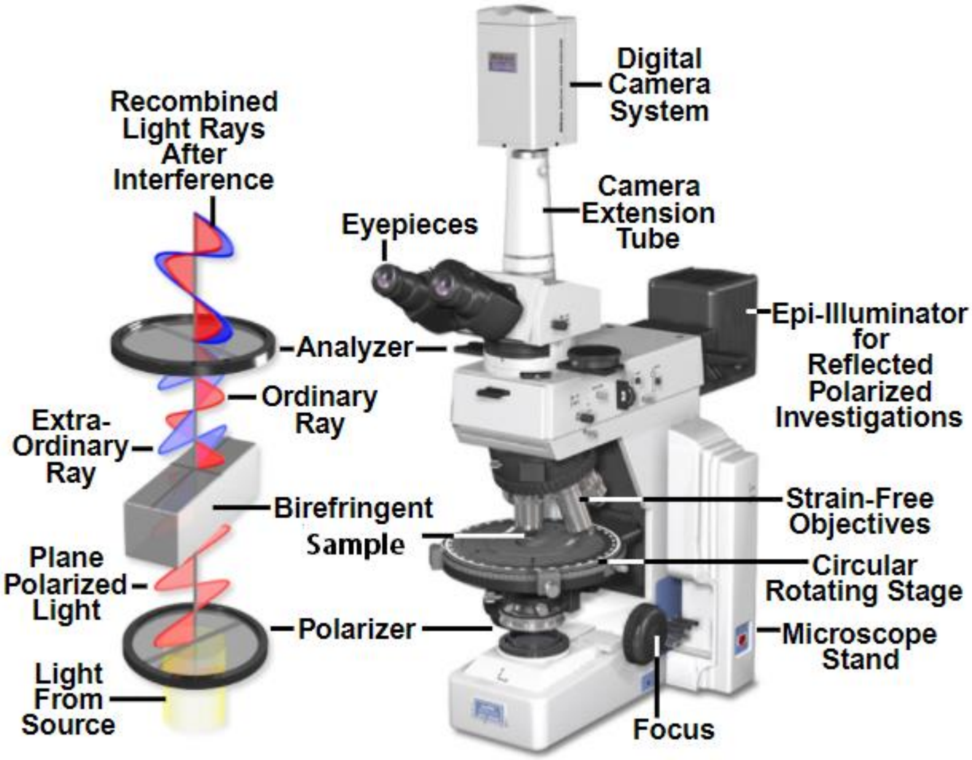
4.2 Polarized Light Microscope

Light is an electromagnetic wave. Natural sunlight and nearly every other form of artificial illumination transmits light waves whose electric field vectors vibrate in all perpendicular planes with respect to the direction of propagation [21]. Despite the fact that light waves can vibrate in any direction, they are most commonly characterized as vibrating in two directions at right angles to each other. Any light which vibrates in more than one direction is called ‘unpolarised light’; whereas, a light wave that vibrates in a single direction is called ‘polarised light’. The direction of light vibration is not detectable by the human eye. A light polarizing microscope is able to convert unpolarized light into polarized one. One technique for achieving this would be by absorbing light vibrational movement in one specific direction.

Polaroid filters are small crystallites of iodoquinine sulfate oriented in the same direction and embedded in a polymeric filter. This embedding is important because it prevents migration and change in the orientation of the crystals [25]. The polarized light microscope is equipped with both a polarizer and an analyzer. The polarizer is positioned in the light path somewhere before the sample, and the analyzer (a second polarizer) is placed in the optical pathway between the objective rear aperture and the observation tubes or camera port. Image contrast arises from the interaction of plane-polarized light with a birefringent (or doubly-refracting) sample to produce two individual wave components that are each polarized in mutually perpendicular planes [22]. The velocities of these components, referred to as ordinary and extraordinary wavefronts, differ and change depending on the sample's propagation direction. After exiting the sample, the light components become out of phase, but are recombined with constructive and destructive interference when they pass through the analyzer.

Figure 8 depicts these ideas for a wavefront field created by a hypothetical birefringent sample. In addition, the image depicts the key optical and mechanical components of a contemporary polarized light microscope. [23]

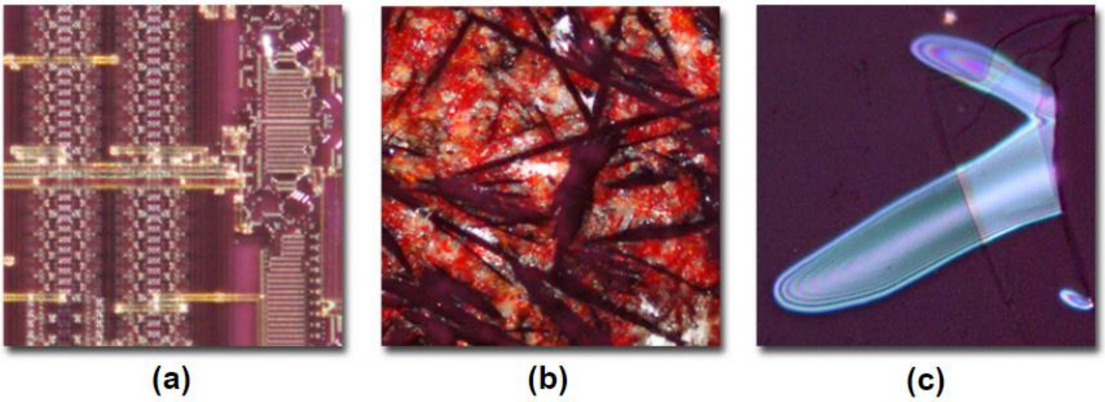
Figure 8 *Polarized Light Microscope Configuration*



Note: Source Robinson, P., & Davidson, M. (n.d.). Polarized Light Microscopy. Retrieved from https://www.microscopyu.com/techniques/polarized-light/polarized-light-microscopy

Both reflected (incident or epi) and transmitted light can be utilized in polarized light microscopy. [24] Reflected light is very suitable for the study of opaque materials such as mineral oxides and sulfides, ceramics, metals, alloys, composites, and silicon wafers. Reflected light techniques require a specific set of objectives that have not been corrected for viewing through the cover glass, and those for polarizing work should also be strain free. [23]

Figure 9 *Reflected Polarized Light Microscopy*



Note: Source Robinson, P., & Davidson, M. (n.d.). Polarized Light Microscopy. Retrieved from https://www.microscopyu.com/techniques/polarized-light/polarized-light-microscopy

Illustrated in Figure 9 is a series of reflected polarized light photomicrographs of typical sample images utilizing this technique. On the left (Figure 9 (a)) is a digital image revealing surface features of a microprocessor integrated circuit. Birefringent elements employed in the fabrication of the circuit are clearly visible in the image, which displays a portion of the chip's arithmetic logic unit. The blemished surface of a ceramic superconducting crystal (bismuth base) is presented in Figure 9 (b), which shows birefringent crystalline areas with interference colors interspersed with grain boundaries. Metallic thin films are also visible with reflected polarized light. Figure 9 (c) illustrates blisters that form imperfections in an otherwise confluent thin film of copper (about 0.1 micron thick) sandwiched over a nickel/sodium chloride substrate to form a metallic superlattice assembly. [23]

4.3 Applications of polarized microscopy

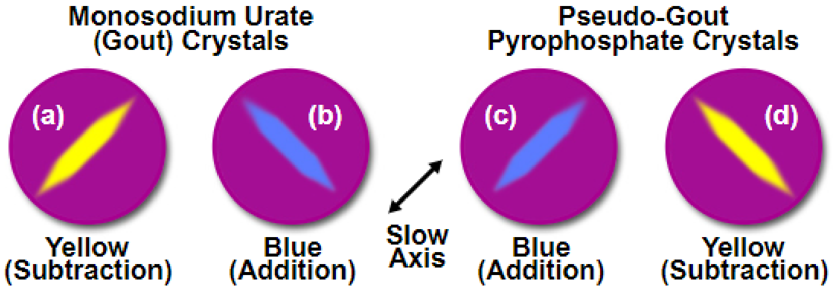
Polarized microscopy is mostly used to examine rocks and minerals in the area of geology. Aside from that, it may be utilized in medicine, chemistry, biology, and on occasion even in metallurgy. [26] Samples that are readily examined between crossed polarizers originate from a variety of natural and synthetic sources and include gout crystals, amyloid, muscle tissue, teeth, solid crystals, liquid crystals, fats, glasses, metals, alloys, among others. Minerals, polymers, ceramics, wood, urea, natural and synthetic fibers with birefringent characteristics, cellophane, as well as plant and insect sample and fish scales, are the finest materials to examine. [23] It is possible to determine the color absorption, structure, composition, and refraction of light in both isotropic (gases and liquids with the same refractive index) and anisotropic substances using polarizing microscopy. [26]

4.3.1 Applications in medicine

One of the most common medical applications for polarized light microscopy is the detection of gout crystals (monosodium urate) with a first order retardation plate. This practice is very common and many microscope manufacturers provide a **gout kit** attachment for their laboratory brightfield microscopes. Gout is an acute, recurring illness characterized by severe inflammation of the joints, particularly in the feet and hands, caused by the precipitation of urate crystals. [27]

During inspection, several drops of fresh synovial fluid are sandwiched between a microscope slide and cover glass and sealed with nail polish to prevent drying. After the sample has been prepared, it is examined between crossed polarizers with a first order retardation plate inserted into the optical path.

Figure 10 *Interference Colors in Gout and Pseudo-Gout Crystals*



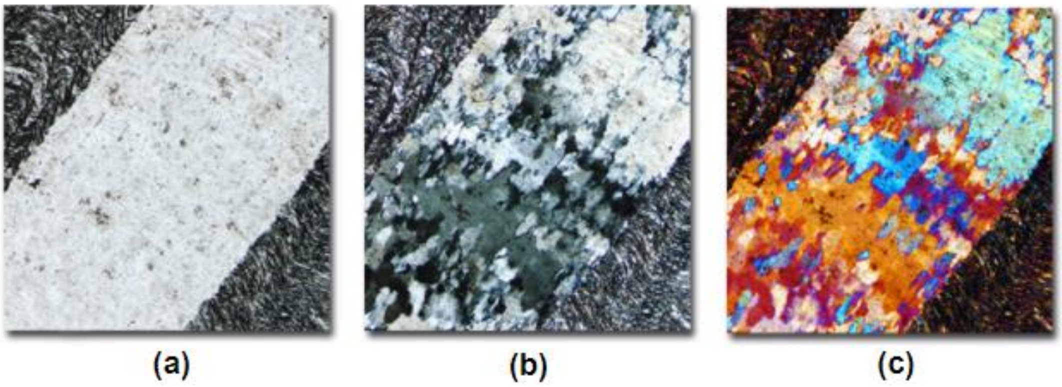
Note: Source Robinson, P., & Davidson, M. (n.d.). Polarized Light Microscopy. Retrieved from https://www.microscopyu.com/techniques/polarized-light/polarized-light-microscopy

Monosodium urate crystals grow in elongated prisms that have a negative optical sign of birefringence, which produces a yellow (subtraction) interference color when the long axis of the crystal is oriented parallel to the slow axis of the first order retardation plate (Figure 10 (a)). When the crystals are rotated through 90 degrees the interference color is blue (addition color; Figure 10 (b)). In contrast, pseudo-gout pyrophosphate crystals, which have similar elongated growth characteristics, display a blue interference color (Figure 10 (c)) when oriented parallel to the slow axis of the retardation plate and a yellow color (Figure 10 (d)) when perpendicular [23]. The sign of birefringence can be used to distinguish between gout crystals and pyrophosphate crystals. Another way for Gout to be identified with polarized light microscopy is through thin sections of human tissue prepared from the extremities. In the medical profession, polarized light can be used to detect amyloid, a protein produced by metabolic deficits and accumulated in various organs (spleen, liver, kidneys, brain), but not in normal tissues. [28]

4.3.2 Applications in geology

Another application that polarized light microscopy has is in the field of geology. Examining geological thin slices with polarized microscopy may tell a lot about how the rock was produced, in addition to providing information on component minerals. Phyllite, a metamorphic rock, clearly shows the alignment of crystals under the effects of heat and stress. Small-scale folds are visible in the plane-polarized image (**Figure x (a)**) and more clearly defined under crossed polarizers (**Figure x (b)**) with and without the first order retardation plate. The crossed polarizers image reveals that there are several minerals present, including quartz in gray and whites and micas in higher order colors. The alignment of the micas is clearly apparent. Addition of the first order retardation plate (**Figure x (c)**) improves contrast for clear definition in the image. [23]

Figure 11 *Phyllite Thin Section in Polarized Light*



Note: Source Robinson, P., & Davidson, M. (n.d.). Polarized Light Microscopy. Retrieved from https://www.microscopyu.com/techniques/polarized-light/polarized-light-microscopy

4.4 Stereomicroscopy History

Cherubin d'Orleans invented and built the first stereo microscope in 1671, although it was a pseudo stereoscopic construction with many faults. Picture erection was only possible with the use of extra lenses, and the right-side image was projected into the left eyepiece and vice versa.[29] It took over 150 years for further work on stereomicroscopy to be carried out after Sir Charles Wheatstone's thesis on binocular vision. The first real stereomicroscope was built in the mid-19th century by Francis Herbert Wenham. His design was using a prism to split the light beam. [30] In the early 1890's, Horatio S. Greenough developed a stereo microscope which was an alternative design to the CMO (common main objective) microscope. Similar to the design which Father d'Orleans had made, Greenough's microscope used two distinct but identical optical paths. He reached out to Carl Zeiss Company with his design where the Zeiss engineers slightly changed the plans - Greenough had designed a lens ascending system to ensure correct orientation of the final image, but at Zeiss, this was replaced with image-correcting prisms. Even today, stereo microscopes are still based on the 'Greenough principle'. [31]

Since then, stereo microscopes have developed into standard equipment in most laboratories. Items such as cameras, fiber optic lighting systems, and computer screens have been incorporated into stereo microscopes. The advent of digital cameras has greatly simplified the way of microscopic observation and image recording. Before that, photomicrography was difficult and time-consuming for researchers, who wasted time learning the process of choosing the right film, determining the exposure time, and developing the photos. In order to reduce the time spent by researchers, photomicrography equipment continues to evolve. [32]

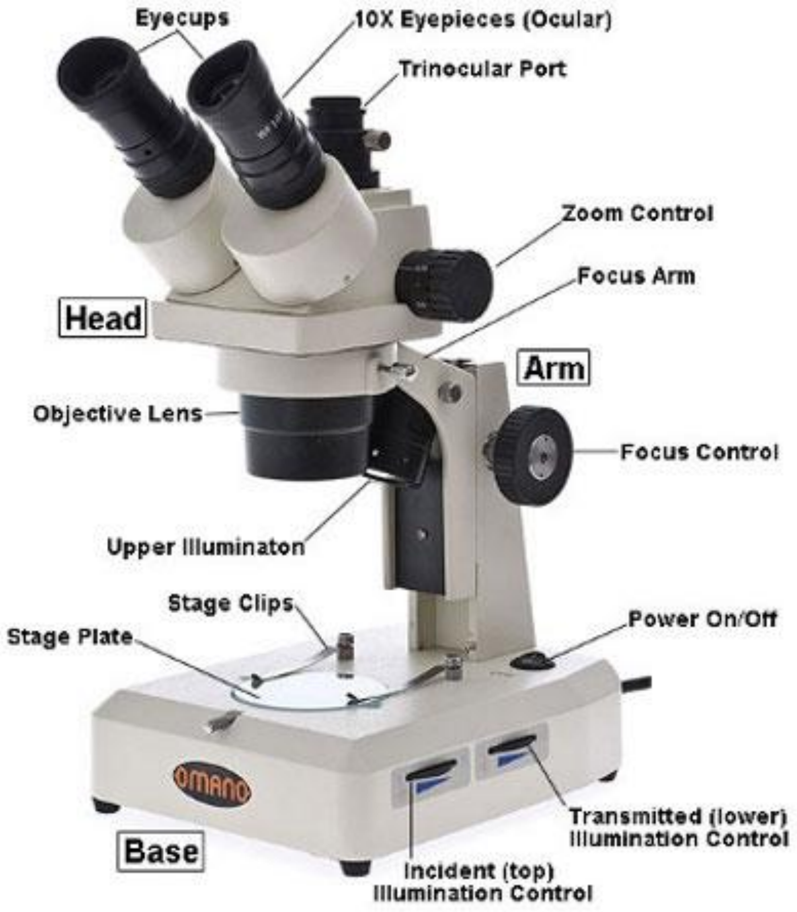
4.5 Stereo microscopes

A stereo microscope is an optical microscope that allows the operator to examine a sample in three dimensions at a low magnification. The main difference of stereo microscope from the compound light microscope, is that it has separate objective lenses and eyepieces. As a result, each eye has two distinct optical pathways. The various angling perspectives for the left and right eye generate three-dimensional images. [33] The two objectives and two eyepieces provide the eyes with slightly different viewing angles. The left and right eyes are viewing the same image, but in distinct ways.

A stereo microscope has three key parts [34]:

- Viewing Head/Body that holds the optical components in the upper part of the microscope
- Focus Block that joins the microscope head to the stand and makes it possible for the microscope to focus
- Stand that supports the microscope and houses any integrated illumination.

Figure 12 Stereo microscope Components



Note: Source Stereo Microscope Parts. (n.d.). Retrieved from https://www.microscope.com/education-center/microscopes-101/stereo-microscope-parts

The additional parts of a stereo microscope include eyepieces or oculars, eyepiece tubes, diopter adjustment ring, objective lenses, focus control, working stage, stage clips, and transmitted illumination. Below these components are briefly explained.

- **Eyepieces**, also known as Oculars, are the lenses that you see through at the top of the microscope. Standard eyepieces typically have a 10x magnification capability. Eyepieces of different powers, ranging from 5x to 30x, are offered as options. Above the objective lens, the eyepiece tube holds the eyepieces in position.
- A **diopter** is an adjustment ring that adjusts for differences in our vision in one or both eyes. Binocular microscopes may also swivel (Interpupillary Adjustment) to adapt varying distances between people's eyes..
- **Objective Lenses** are the primary optical lenses on a microscope. In a low power microscope, they give fixed or zoom magnification. Zoom magnification is usually available in a Greenough design or with a Common Main Objective.
- **Focus Control** Majority of stereo microscopes have only coarse focus controls.
- **The Working Stage** is where the sample to be inspected is placed. Since lower magnification powers require motions that are less subtle than high power microscopes, pole and track stands have simple stages
- **Stage Clips** are used in cases when there is no mechanical stage.
- **Transmitted Illumination.** Since most samples examined on a stereo microscope are opaque, a top light (Transmitted Illumination) is used to shed light on the sample. It's not very typical but some stereo microscopes also include a bottom light (Incident Illumination) [34].

4.6 Applications of Stereo Microscopy

Stereo microscopes may be utilized in a number of applications due to their capacity to observe three-dimensional structures. An operator can engage on the sample they're analyzing while it's still being viewed in real time. [35] These Microscopes have a wide range of applications in a number of fields such as education (biology, geology , botany, chemistry, and zoology), medicine, and pathology. Another application of this device is in the observation of opaque thick objects where the emission of light is impossible, for example rocks or coins . Stereo Microscopes are widely used in several industries. Worth mentioning is the semiconductor production, circuits, textiles, metallurgy and different enterprises that require assembly and assessment of small parts.

4.6.1 Surgical and Medical Applications

A well known use of stereomicroscope is in the medical field of surgery. Usually its being used in laboratories as a tool to examine and perform medical procedures in specimens. It is heavily used in sectioning operations and microsurgery [35]. Stereo Microscopes can aid researchers and professionals doing surgical study on tiny animals and rodents, such as mice, rats, hamsters, and other rodents, for developmental biology and medical investigations. The use of stereo microscopes is intended to make work steps more efficient and cost-effective. It is critical to eliminate variability through improved surgical procedures and apparatus in order to maximize outcomes and lower study expenses.

Rodents and small animals are often used as model organisms to study and evolve treatments for diseases and medical issues which affect humans, [36] i.e., cancer, stroke, neurodegenerative sickness, liver ailment, joint inflammation, diabetes, and so on. Mice, rats, hamsters, guinea pigs, rabbits, and other rodents and small animals are often used in these experiments because of their anatomical, histological, hormonal, and genetic similarity to humans [37].

5 METHODOLOGY

In this section are presented methods used thus far concerning physical inspection of Integrated Circuits. Within the section are depicted standards used and the procedures followed regarding optical inspection.

5.1 Chip inspection Standards

Currently there are several standards that are utilized in order to detect counterfeit parts. SAE International has been responsible setting these standards through the G-19 Counterfeit Electronic Parts Committee [18]. Their standards aim to reach three sectors of the industry: distributors, users, and test laboratories. These standards are as follows:

1. AS5553—Counterfeit Electronic Parts; Avoidance, Detection, Mitigation, and Disposition [19];
2. ARP6178—Fraudulent/Counterfeit Electronic Parts; Tool for Risk Assessment of Distributors [38];
3. AS6081—Fraudulent/Counterfeit Electronic Parts: Avoidance, Detection, Mitigation, and Disposition—Distributors Counterfeit Electronic Parts; Avoidance Protocol, Distributors [39] (intended for independent distributors and brokers);
4. AS6496—Fraudulent/Counterfeit Electronic Parts: Avoidance, Detection, Mitigation, and Disposition—Authorized/Franchised Distribution [40]; and
5. AS6171—Test Methods Standard; Counterfeit Electronic Parts [41].

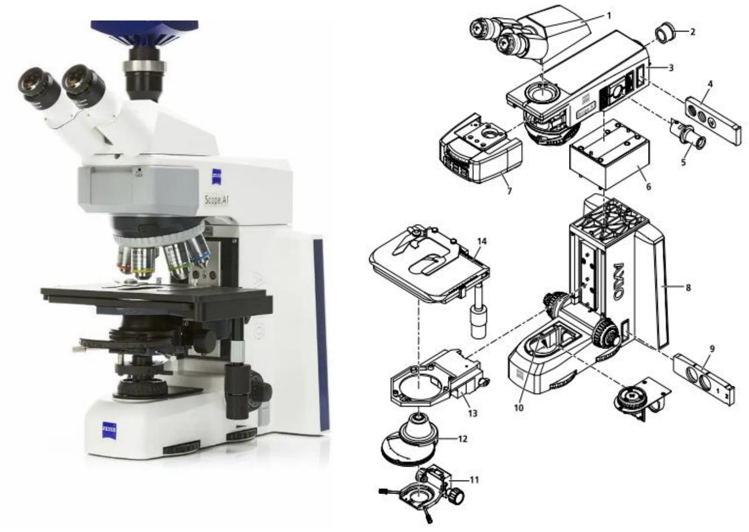
5.2 Method used and the procedures followed

Internal physical testing is used in the procedure of this thesis. Decapsulated Integrated Circuits shall be thoroughly investigated through two different microscopes. All pieces shall be examined with minimal of handling and movement of the circuits. Polarized and Stereo microscopes both from Carl Zeiss industries.

5.2.1 ZEISS Axio Scope.A1

For the polarized microscopy ZEISS Axio Scope.A1 shall be used to take digital images of the decapsulated chips. It be used with reflected and transmitted light techniques such as Brightfield, darkfield, polarization, DIC, circular DIC, fluorescence, and phase contrast. This microscope is equipped with two objectives used during experimentation consisting on N-Achroplan 5x and 20x ECPlan-Neofluar magnification. Images are displayed in Axio-Vision SE64 software and it has options to process, analyze, and store images.

Figure 13 *Zeiss Axio Scope*



1 Tube
2 Achromatic illumination adapters
3 Upper stand part
4 Filter slider reflected light
5 Adjustment aid
6 Adapter
7 Reflector insert
8 Lower stand part
9 Filter slider transmitted light
10 Filter in the filter wheel transmitted light
11 Condenser carrier
12 Condenser
13 Stage carrier
14 Stage

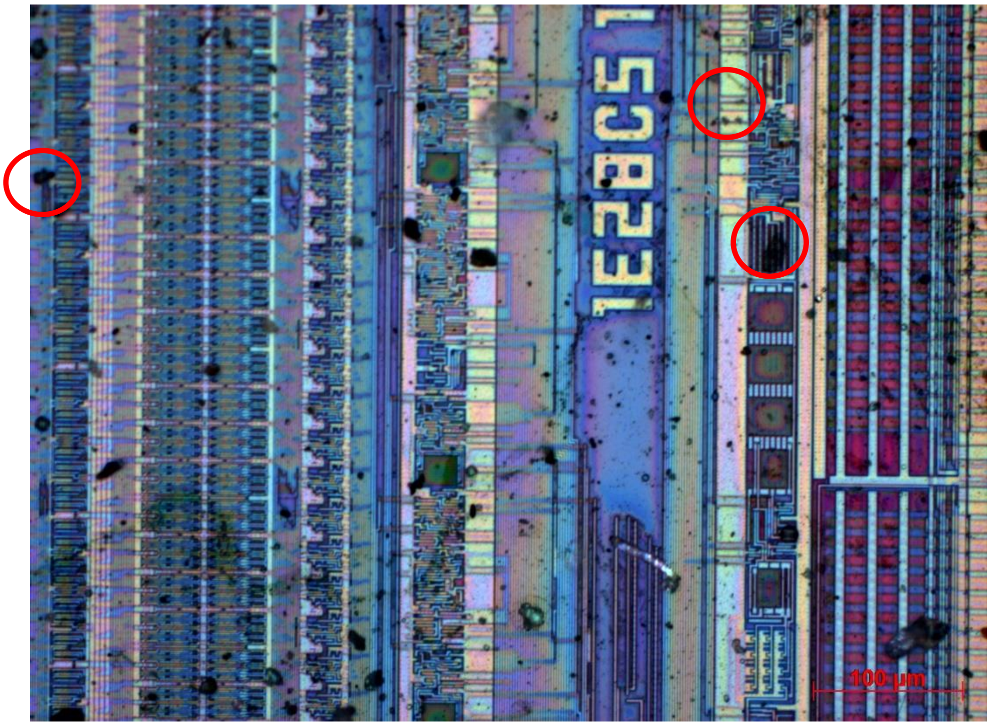
Note Source: https://www.manualslib.com//Zeiss_Axio-ScopeA1-materials-brochure

The Zeiss Axio Scope A1 microscope is designed for universities, research laboratories, industrial and medical applications. It is a popular modular member of the Zeiss microscope series. A unique aspect of its design is that the top and bottom of the mount can be separated with 30mm and 60mm spacers, with a total distance of up to 110mm, to allow inspection of large samples directly under the objective lens [42]. This has made it very convenient to place different types on Integrated Circuits under inspection.

5.2.1.1 Experimenting procedure

Images retrieved from the microscope clearly show damaged parts of the die. They contain scratches, corrosions and blistering. As denoted in red circle, blisters and scratches on the surface of the chip are noticed. There can be seen some damages around the bonding wires which may suggest rebounding.

Figure 14 *Axio Scope A1 20x ECPlan-Neofluar images*

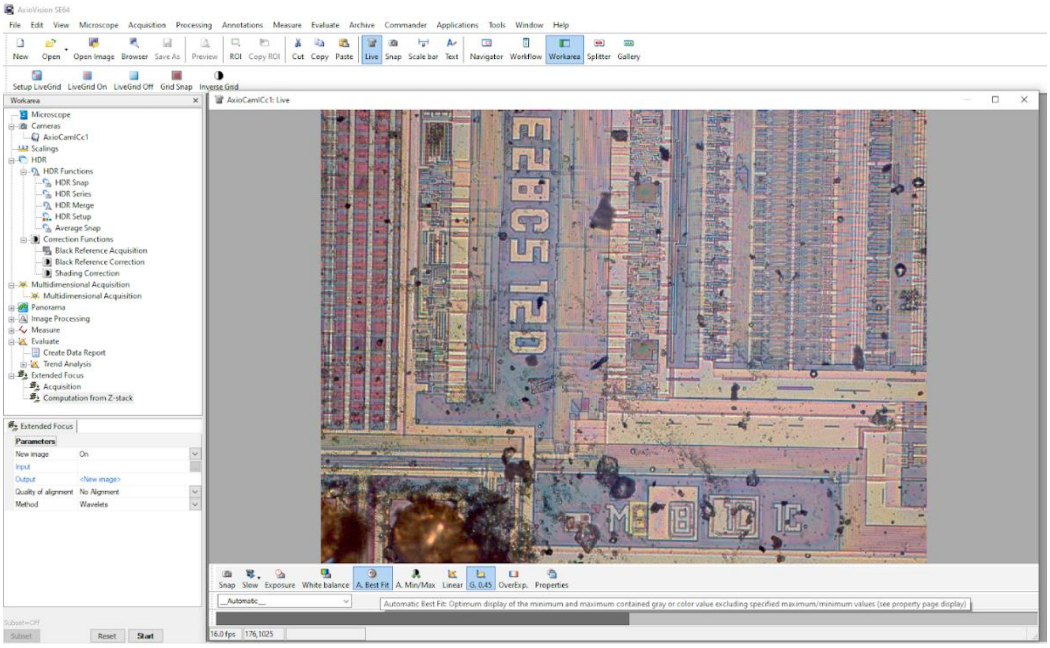


Note*: Images taken with Axio Scope A1 20x ECPlan-Neofluar objective, Epi-Pol, showing damages on the surface of the decapsulated chip revealing possible counterfeiting*

5.2.1.1.1 Panorama Modulus

The 20x ECPlan-Neofluar objective offers much higher magnification and better details from sections of the chip being inspected. Since images coming from this objective are in small sections it is hard to have general view of the whole chip. A module named Panorama makes it possible to create a large image out of smaller sections that can be retrieved and stitched together live from the camera.

Figure 15 *AxioVision*



Note: Objective: 20x ECPlan-Neofluar – Polarization – Best Fit

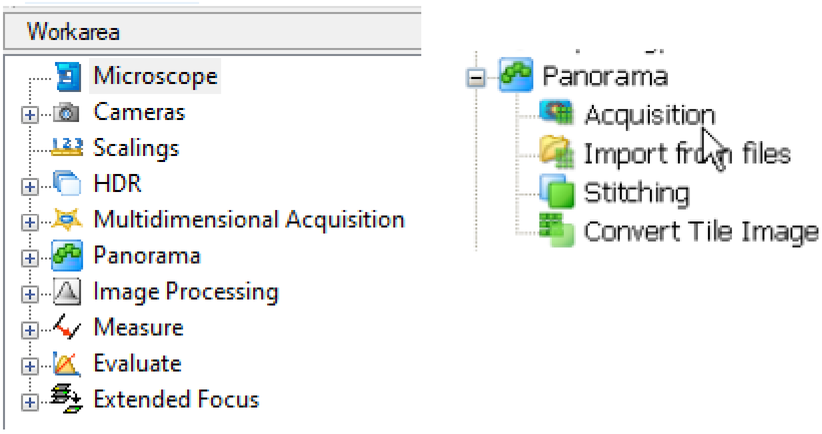
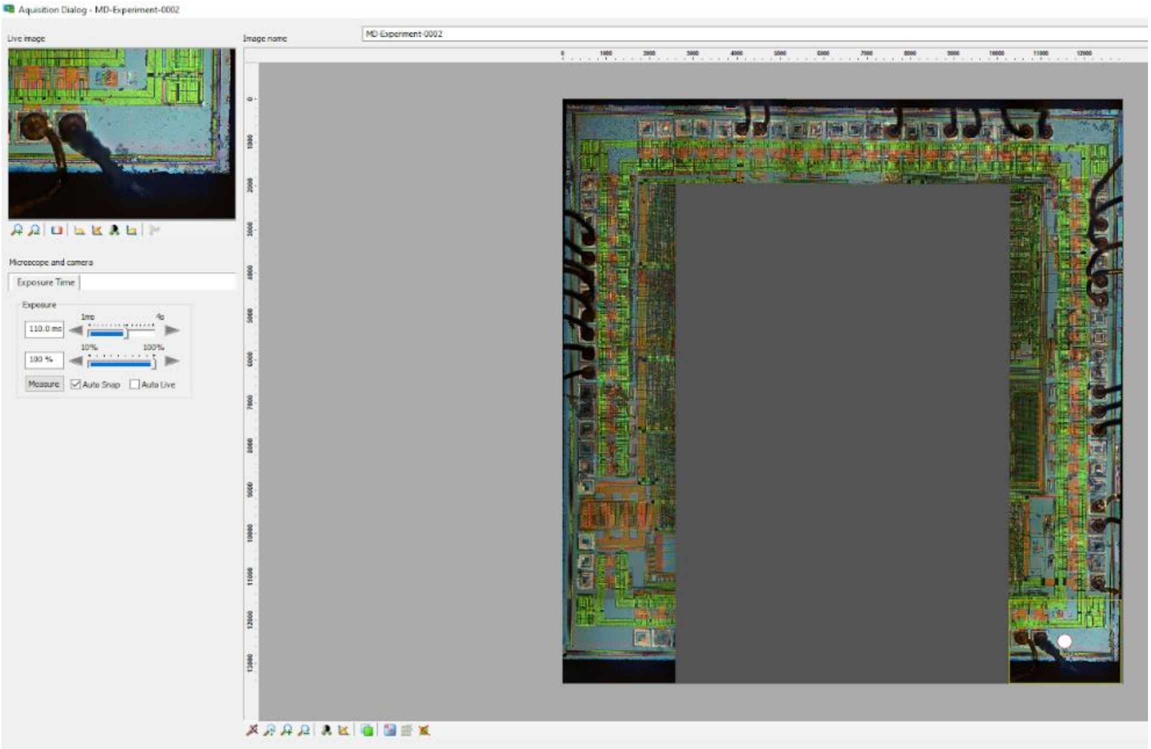


Figure 16 *Panorama module*

After several tried of stitching the sections together the most suitable way is to take retrieve imagines walking through the corners along the perimeter and finally towards the inner part of the chip. The outer side of the chip works as a path to follow and makes it possible to lock and capture the majority of the chip area without many mistakes. Even though the tiles can be moved or deleted, acquiring the right positioning in the initial capturing step makes the process easier and more efficient.

Figure 17 Image *Acquisition in AxioVision*



Aquisition Dialog - MD-Experiment-0002

Image name: MD-Experiment-0002

Exposure: 110.0 ms

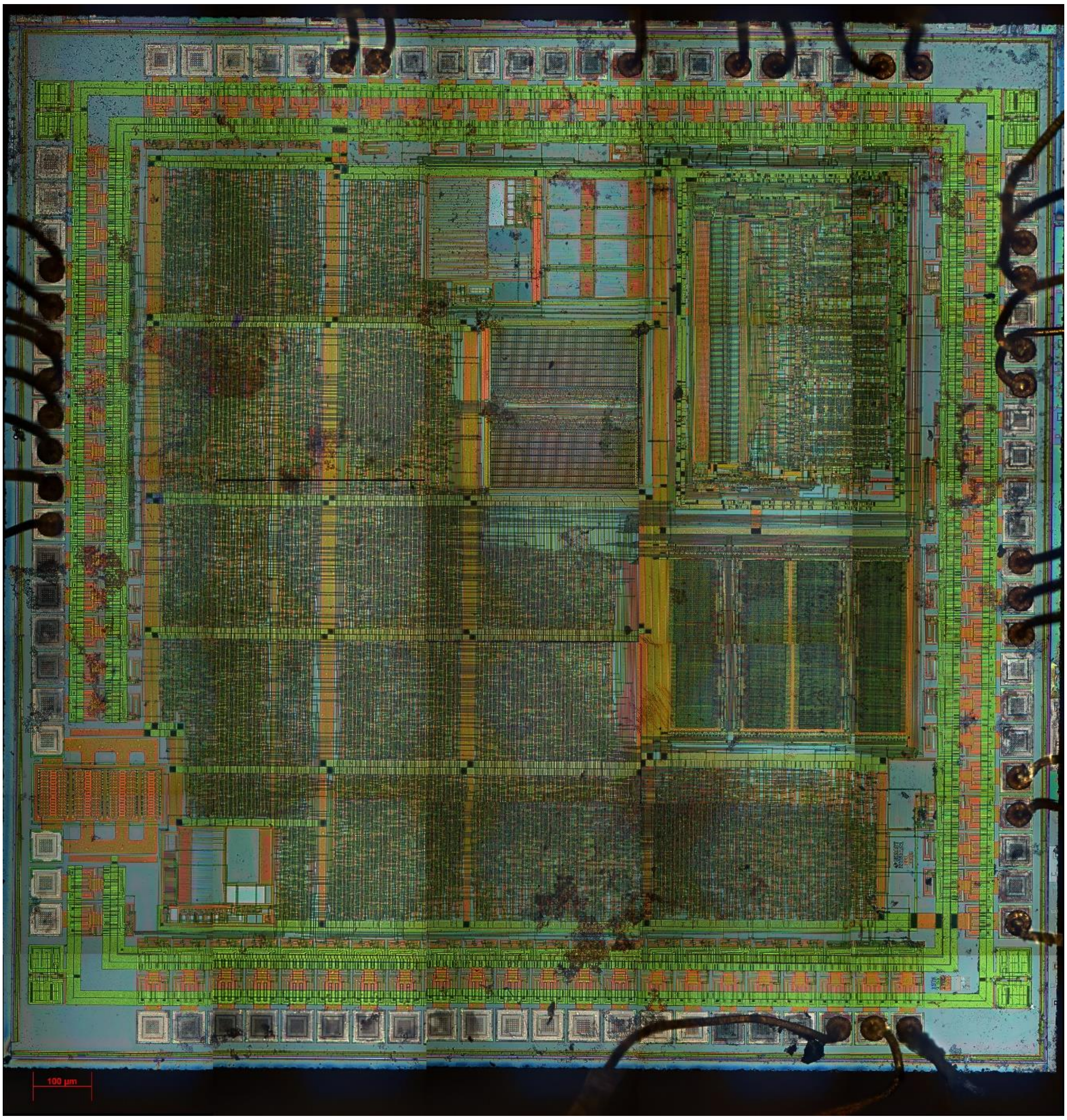
100 %

☑ Auto Snap ☐ Auto Live

Note: Several trials showed that its more suitable to capture images through the sides and making the way in. It lowered the misalignment possibilities.

The final image has a high level of magnification and the quality of each section is maintained. This technique is suitable to get a clear imagine on where labeling or any other chip information is positioned. Zooming into every section will produce a high-quality image that is not lost when all tiles are stitched together. Below the final imagine is showed:

Figure 18 *Final image composed*



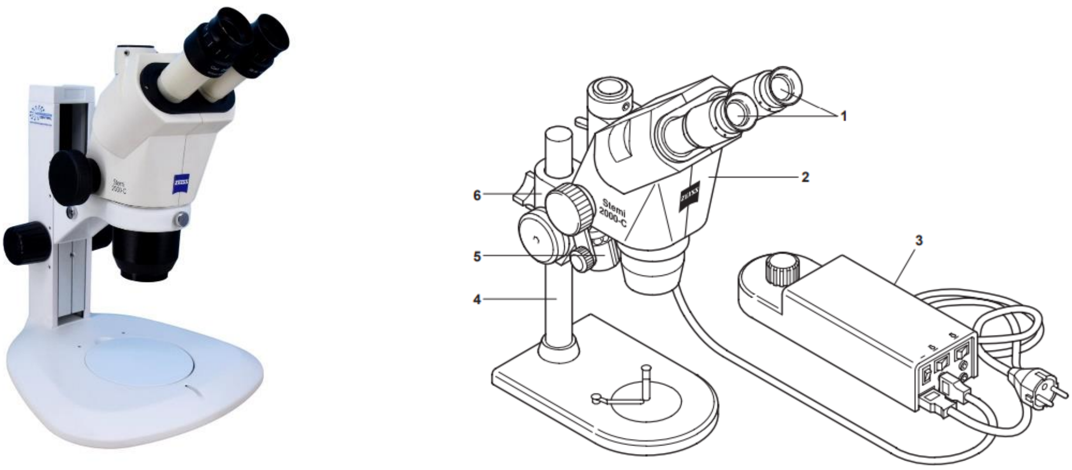
Note: Final imagine retrieved from several sections of the chip using the *20x ECPlan-Neofluar objective and Panorama Module, scale 100 µm*

This technique on the other hand is time consuming and when having a very high number of tiles to be captured, the chance of them being not perfectly aligned increases. In average it takes 40 minutes to capture and another 10 -15 minutes to properly align the sections. Since the final image contains very valuable information visually and in content, it can be used not only for counterfeit detection purposes but also for educational and marketing purposes.

5.2.2 Zeiss Stemi 2000-C

The zoom range of the Zeiss Stemi 2000-C microscope is 0.65x 5.0x. With the supplied 10x/ 23mm FOV eyepiece, the total magnification of this microscope is 6.5x - 50x. It has one click to stop at 0.65, 0.8, 1.0, 1.25, 1.6, 2.0, 2.5, 3.2, 4.0, and 5.0 zoom settings. The trinocular viewing head allows you to add cameras to the microscope [43]. The camera used in the laboratory is a Canon DS126191.

Figure 19 *Stemi 2000-C*



Note: Source "Stemi 1000/2000/2000-C Stereo Microscopes https://neurophysics.ucsd.edu/Manuals/Zeiss/Stemi%201000-2000-2000C%20Stereomicroscope%20operating%20manual.pdf

Figure 19 shows the principal assemblies of the Stemi 2000-C.

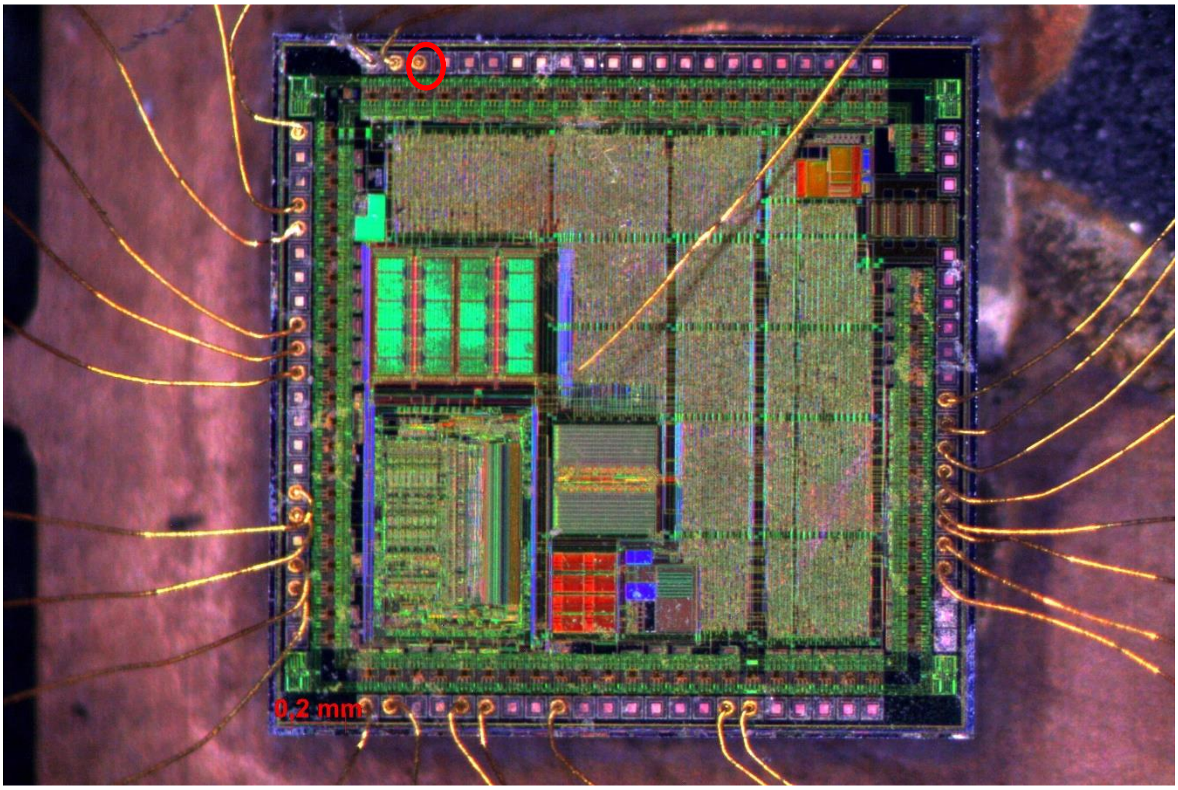
- Stand S with 260 mm column (1-1/4)
- Stemi mount with drive for column 32 (1-1/6)
- Stemi 2000-C microscope body (1-1/2)
- Eyepieces W-PL 10x/23 Spec. foc. (1-1/1) with eye cup
- Built-in 6 V, 10 W halogen vertical illumination (1-1/5) with 115/230 V – 6 V 50 VA power supply (1-1/3) [44]

5.2.2.1 Experimenting procedure

Zeiss Stemi 2000-C microscope is equipped with a low magnification ability, but it is able to produce sharp images, distortion free, and with a high resolving power. From the images captured from the microscope it is possible to depict different parts of the chip like connections, bonding wires, lead frame etc. The positioning of the die inside the wafer can be spotted in the images and we can draw conclusions regarding authenticity based on it.

In the image below we can see one of the bonding wires is missing. It could be warning for a counterfeited part, but it also could have happened during the decapsulation session. It is hard to say anything regarding the surface of the die at this magnification level.

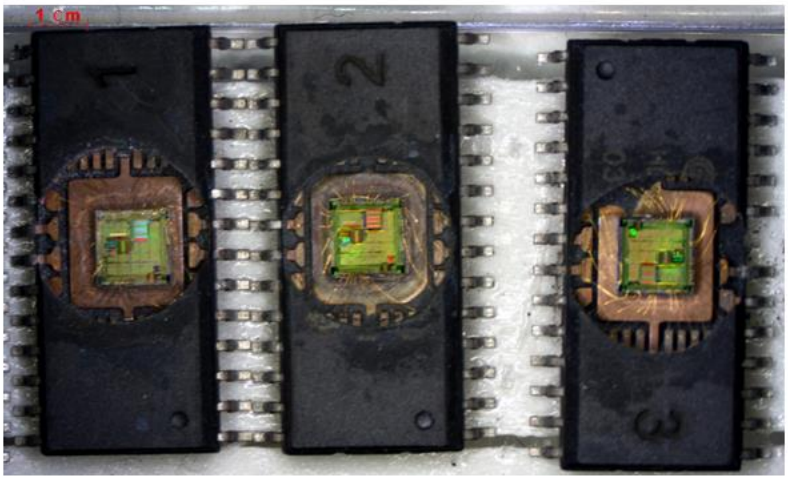
Figure 20 *Zeiss Stemi 2000-C image*



Note: Image captured with Zeiss Stemi 2000-C at 50 x magnification

Since the area between the objective and the sample is relatively big, it gives way to the possibility of inspecting several samples at the same time. Up to three IC were able to be retrieved within the frame.

Figure 21 IC under Zeiss Stemi 2000-C

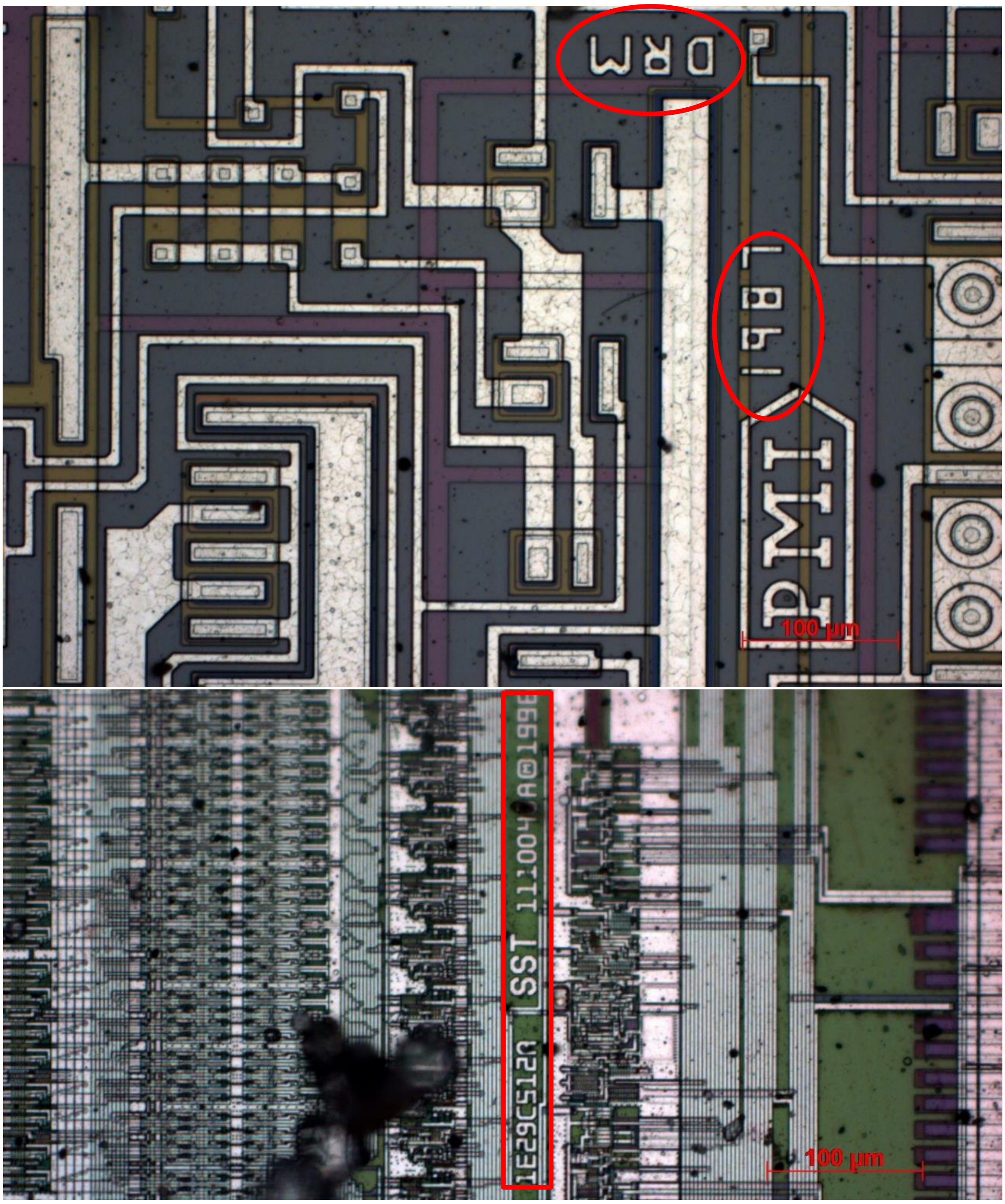


Note: Three integrated circuits can be simultaneously captured under Zeiss Stemi 2000-C

6. RESULTS

This section will provide images captured during the experimental process. The images captured with polarizing microscope ZEISS Axio Scope.A1 are of high quality and contain several information features of the chips under inspection. As illustrated below from the images retrieved logos, labeling, connections and different bonds can be seen and inspected.

Figure 22 *IC under Axio Scope A1*

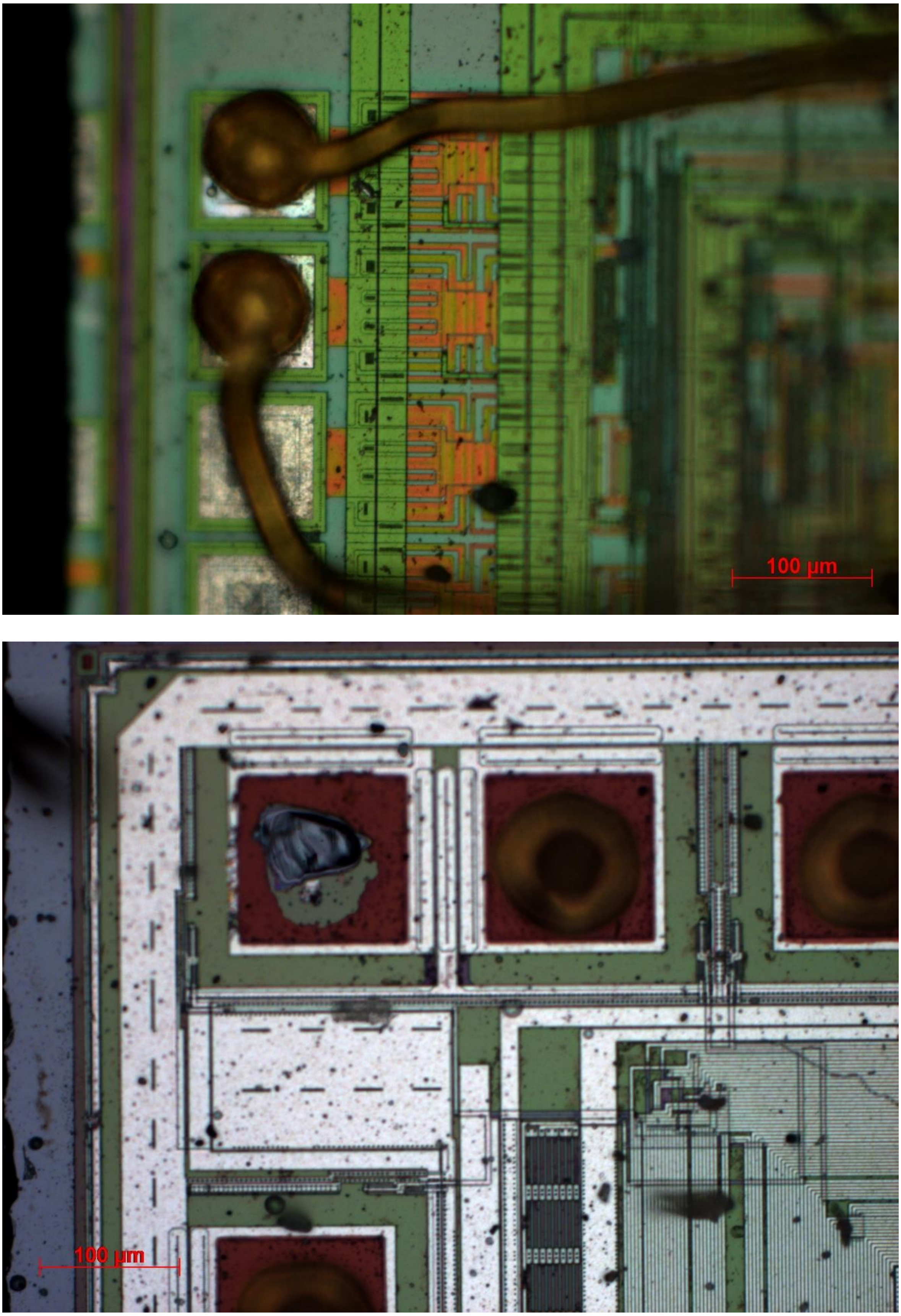


Note: *Images taken with Axio Scope A1 20x ECPlan-Neofluar objective, Epi-Pol*

Figure 23 *IC under Axio Scope A1*

Note: *Images taken with Axio Scope A1 20x ECPlan-Neofluar objective, Epi-Pol*

Figure 24 *IC under Axio Scope A1*



Note: *Images taken with Axio Scope A1 20x ECPlan-Neofluar objective, Epi-Pol*

6.1 Polarizing microscope ZEISS Axio Scope.A1

Polarizing microscopes capture very high-quality images from the decapsulated chip making is possible to spot different damages or evidence that may insinuate counterfeiting. Several chips that were inspected contained scratches, blisters and damages around the bond wires. The 20x ECPlan-Neofluar objective produces images where the damages can be easily pertained to proceed with authentication process.

By using the Panorama Module, the inspection process can be improved. Panorama is very suitable for samples that do not fit into the image frame. A high-resolution overview or panoramic image with pixel accuracy can be formed from a single lens. Even overlapping images can be combined so precisely that all the important details of the sample are recorded in one image. This makes it possible to face a golden piece and a suspected part from a wide angle. The experimenting process resulted that the most efficient way to capture the sections is to start thorough the corners along the perimeter and making the way inside the chip.

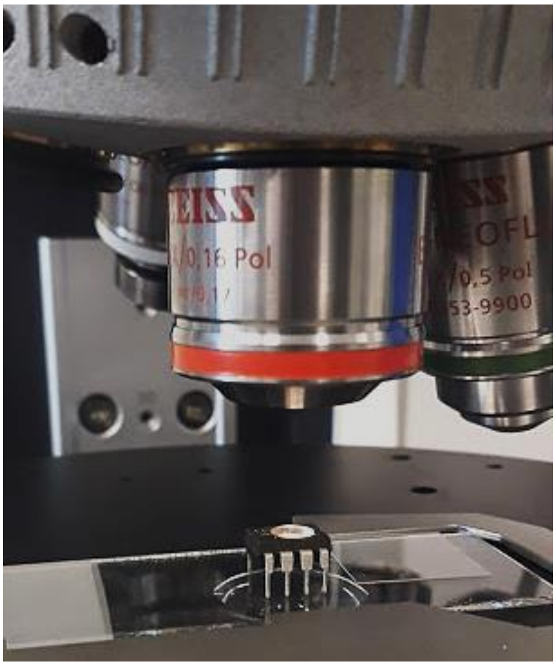
6.1.1 Panorama modulus step by step

In this section the retravel of the images by using the Panorama Modulus will be presented step by step. Images were captured using 20x ECPlan-Neofluar and N-Achroplan 5x objective in ZEISS Axio Scope.A1. AxioVision software displays the live camera from the microscope.

Step I

The sample is placed on the stage and positioned vertically. The objective is selected and rotating it by being careful the specimen is far enough for the tip of the lens not to be scratched or damaged. It is suggested to start with the objective N-Achroplan 5x, get it focused and locate the die. Afterward we rotate to the 20x ECPlan-Neofluar objective, slowly focusing to retrieve a clear image.

Figure 25 *IC position under N-Achroplan 5x objective*



Step II

Once the sample is set and the objective positioned, we should be able to see from AxioVison live camera, how one section of the chip looks like in high magnification. Then we proceed to the Panorama Modulus on the left side of the Work area. The Acquisition Section will come up and now the images will be captured one by one.

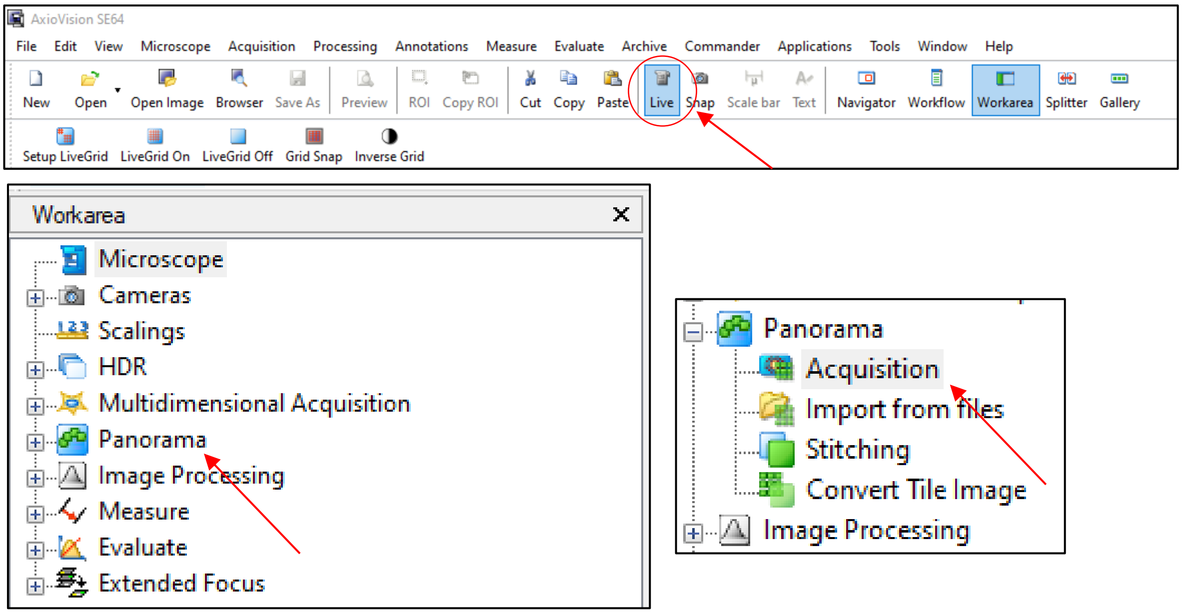
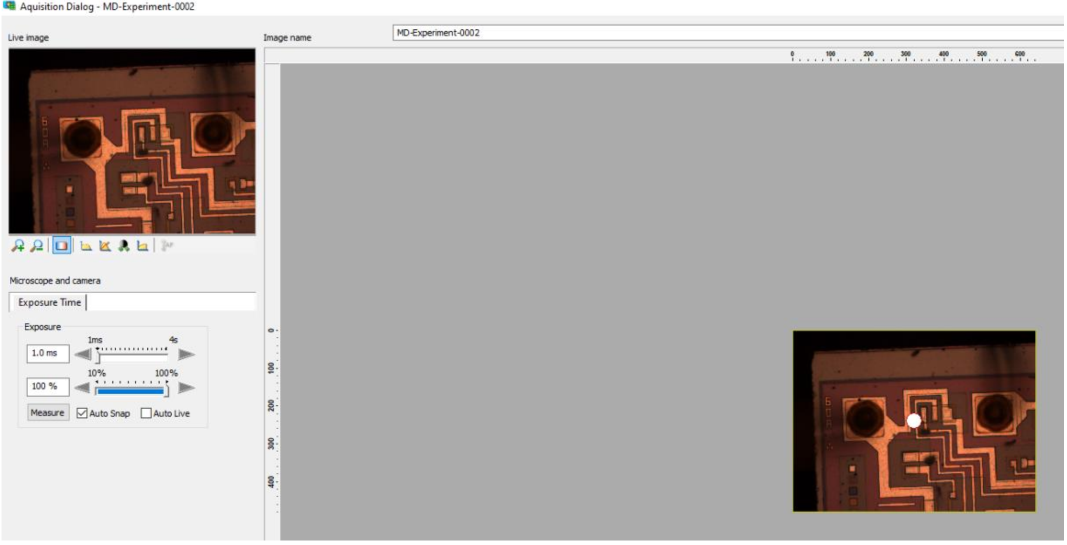


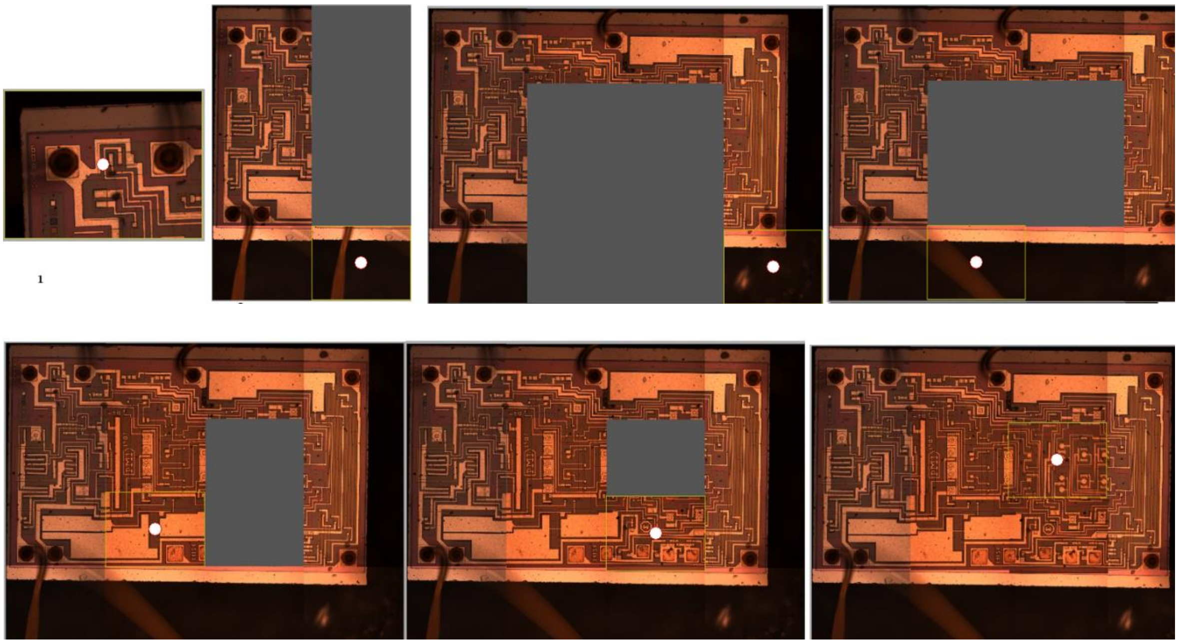
Figure 26 *Acquisition Dialog Menu AxioVision*



Step III

The capturing of the sections is started from the top left corner of the chip and proceeds further down until the whole perimeter of the die is acquired. From that point we proceed with the inner part following the same path. The sections/tiles can be shifted if we are not happy with the capturing. Below we can see all the image acquisition process path from beginning to end. The dot in the image represents the live camera image being captured.

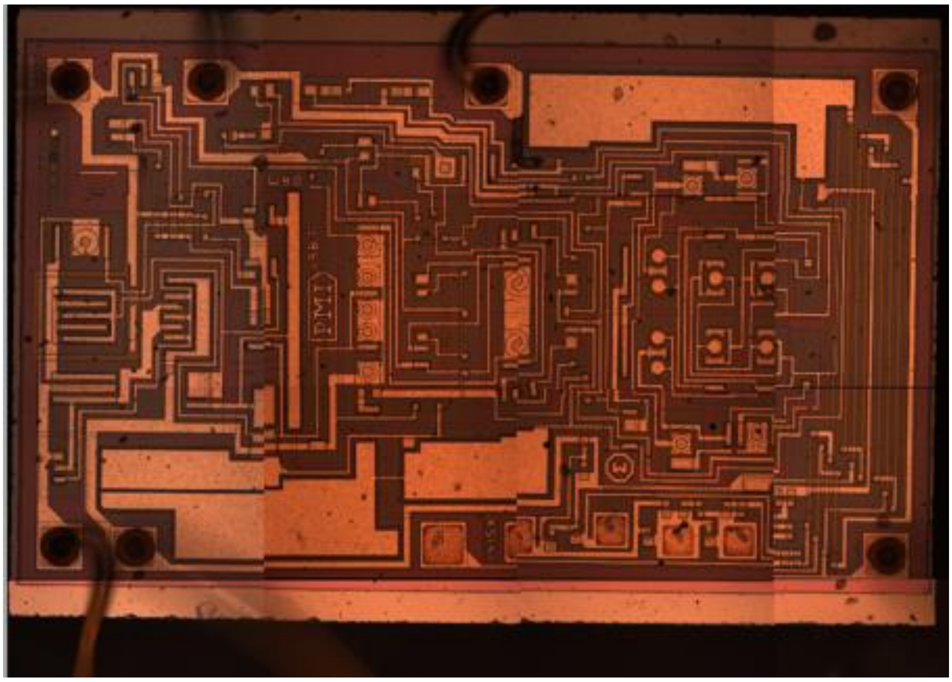
Figure 27 *Image capturing path*



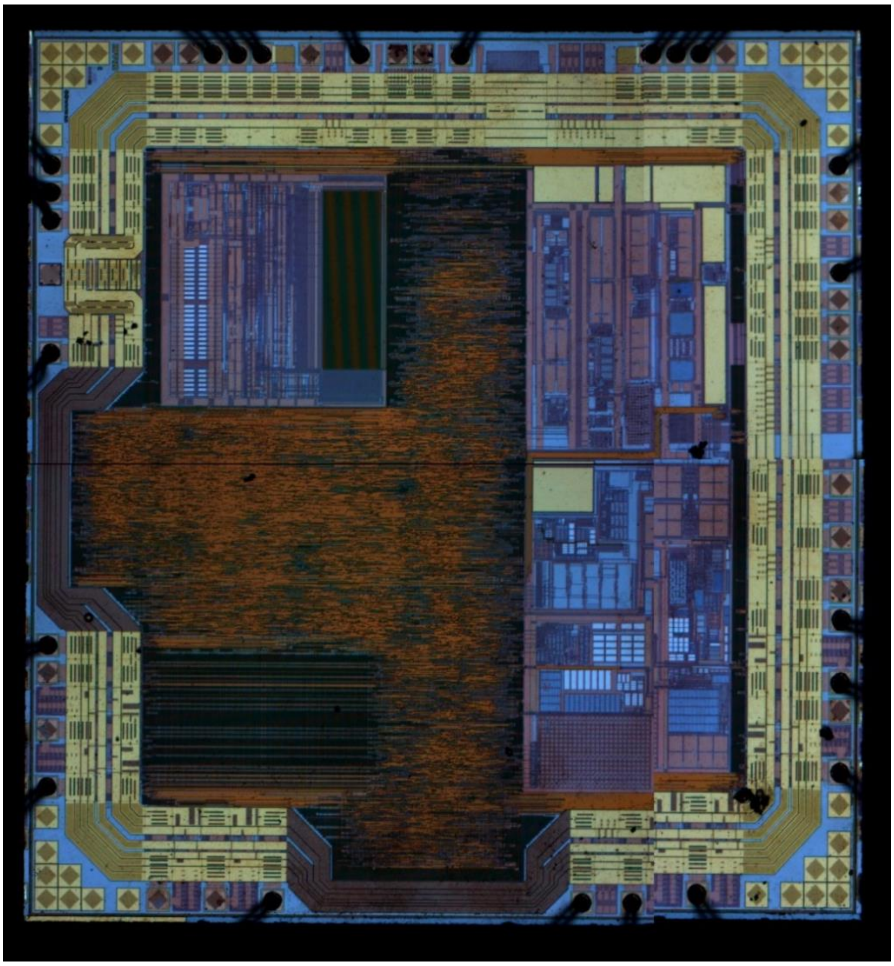
Step IV

After the sections are acquired the stitching process follows. In this step all separated parts captured are combined to create a large image with high quality. By clicking **"OK"** AxioVision makes it possible for the whole image to be created. Below we can see the final image in the end of the session. The image can later be extracted as .JPEG and be used for authentication purposes.

Figure 28 *Images Acquired through Panorama Modulus*



Note: *Images taken with Axio Scope A1 20x ECPlan-Neofluar objective, Epi-Pol, scale 100 μm*

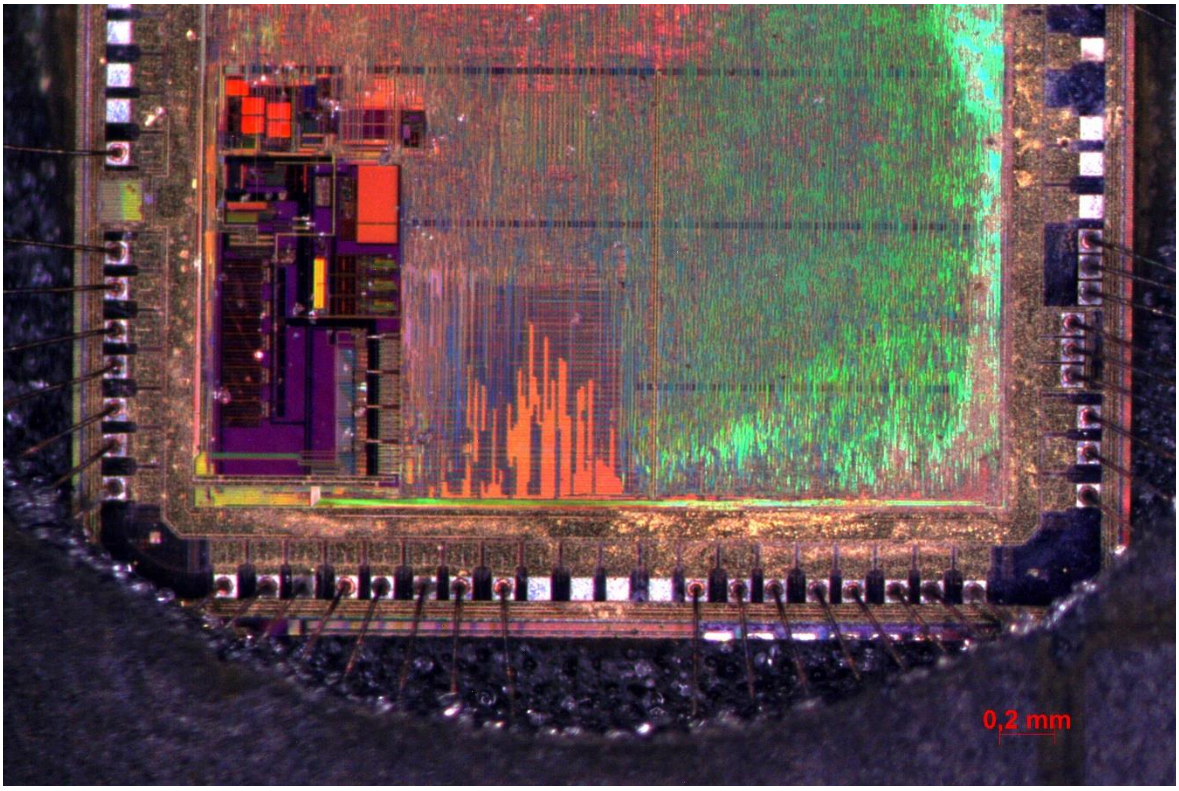


Note: *Images taken with Axio Scope A,1 20x ECPlan-Neofluar objective, Epi-Pol, scale 100 μm*

6.2 Stereo microscope Zeiss Stemi 2000-C

Stereo microscopes are suitable for capturing sharp and distortion free images. Through these images we can retrieve information's like broken bonds or damaged lead frames. Unfortunately, due to the magnification not being high enough the decapsulated chip cannot be inspected in detail to be able to check if the surface has any scratches or anything related to logo or marking.

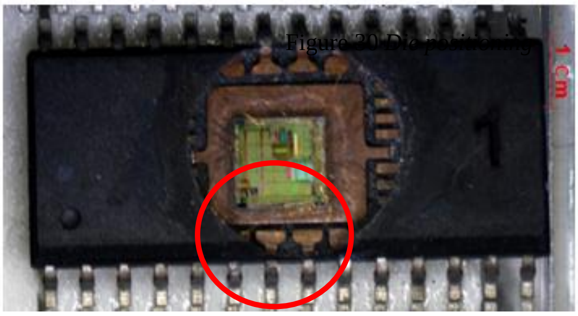
Figure 29 *Zeiss Stemi 2000-C at 50 x magnification*



Note: Image captured with Zeiss Stemi 2000-C at 50 x magnification

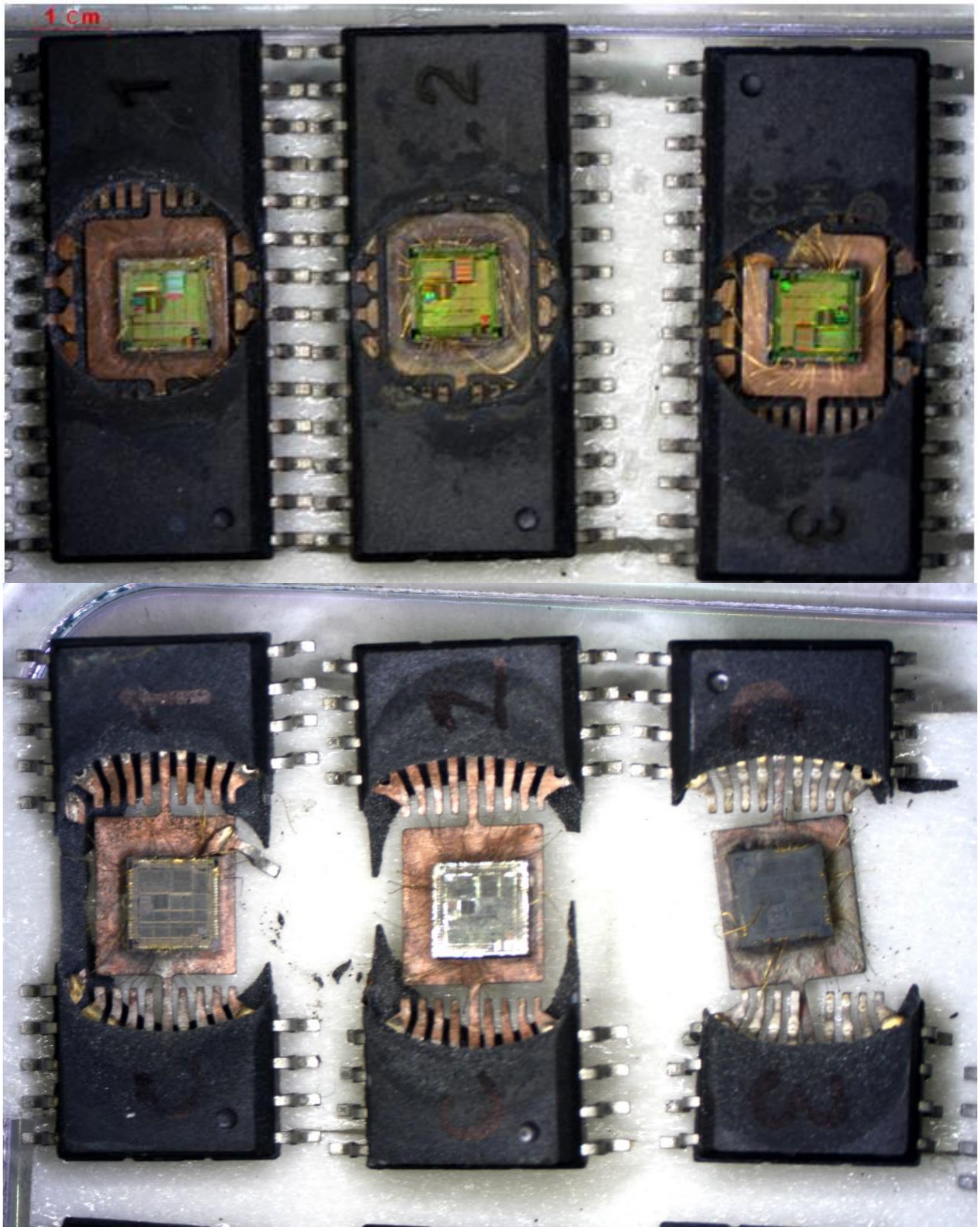
The positioning of the die inside the wafer can be spotted in the images and we can draw conclusions regarding authenticity based on it. In Figure 29 after the IC has been decapsulated, it reveals an uncentered die inside the IC.

Figure 30 *Die positioning*



Another advantage of Stemi 2000-C is the wide area of the objective and the sample. Several samples can be inspected simultaneously at the same time within the same frame. This makes it possible to check a golden piece and a suspected one at the same time.

Figure 31 *Image captured with Zeiss Stemi 2000-C*



Note: The images show the progression of the decapsulation procedure.

7. CONCLUSIONS

Counterfeit electronic components have become a major challenge in today’s supply chain. Detecting and preventing these parts from entering the market is becoming harder and this calls for more methods and tools to face this phenomenon. A polarizing and stereo microscope were used to inspect decapsulated integrated circuits. Polarizing microscope ZEISS Axio Scope.A1 showed high efficiency in reviling scratches, blisters on the surface of the die and damages around the bond wires. The images retrieved clearly reveal logos/markings and connections within the die. All this information can be later used to accept or reject the part as authentic or not. By using the Panorama Module, the inspection process can be improved. This technique became the focus while working with the polarizing microscope. The final image has a high level of magnification and the quality of each section is maintained. It was noticed that it was suitable for different samples and the same procedure could be implemented in each of them.

Stereo microscope Zeiss Stemi 2000-C was suitable of capturing sharp images of the die and get information regarding broken bonds and damages on the lead frame. The positioning of the die inside the IC is not always centered in the images and we can draw conclusions regarding authenticity based on it. Several of the specimens during the experiments reviled uncentered chip inside the wafer. Unfortunately, due to its low magnification, small details like labeling and logos were not visible under it. Stemi 2000-C makes it possible to inspect several circuits at the same time. During the experiments three IC were inspected at the same time. The images showed the chronological evolution of the decapsulation process in several chips and the same approach can be taken when analyzing a golden piece and a suspected component. Having these components parallelly facing in the same screen increases the possibility of finding evidence of possible counterfeiting in the suspicious piece.

7.1 Future recommendations

This research can be used as a starting point for future students wanting to work with optical microcopy to inspect any type of counterfeited components. The methodology used in the polarized microscope can be implemented also in other electrical parts besides IC. Transistors can be decapsulated and inspected for faults or simple for structural purposes. Accordingly, the Stemi 2000- C microscope can be utilized in the future for inspection of larger pieces like hybrid integrated circuit (HIC). The large area between the objective and the table where the specimen is placed, makes room for slightly bigger components.

During this research the main focus was related to counterfeit of Integrated Circuits. I would suggest using the technology of these microscopes also in other contexts. Images retrieved from the microscopes can be used in educational purposes. Many schools or other educational environments that cannot afford powerful microscopes like ZEISS Axio Scope.A1 would be at least able to retrieve images produced from them. Building a large database of high- quality digital images could improve the teaching process in these environments.

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LIST OF ABBREVIATIONS

AC - Alternative Current
C&D- Cooperation and Development
CoC - Certificates of Conformance
DC - Direct current
EU - European Union
IP - Intellectual Property
OMC - Original Component Manufacturer
PCB - Printed circuit boards
SAM- Scanning acoustic microscopy
SEM - Scanning electron microscopy
SoW - Statement of Work
TEM - Transmission Electron Microscopy
FIB - Focused Ion Beams

LIST OF FIGURES

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