Investigating Techniques for Detecting Recycled Integrated Circuits: A Study of Reliability and Accuracy

I. INTRODUCTION

An integrated circuit (IC), usually referred to as a microchip, is a small assembly of transistors, diodes, and other parts, that is intended to carry out a specific task. It is a component of contemporary electronics, serving as a CPU behind numerous gadgets ranging from smartphones to automobiles, and is the go-to option for a variety of applications thanks to its versatile design, dependability, and low power consumption. So, as the demand for ICs increases daily, some unscrupulous third parties seek to produce counterfeit ICs to profit from the situation. In the supply chain, there are seven different types of counterfeit ICs, but in this paper, our focus will be the **recycled ICs**, that make up nearly 80% of all recorded counterfeiting incidents among all the types of counterfeits. Essentially, a recycled IC is a chip that is discarded after its purpose has been served in an electronic device or system and is then reintroduced into the market, changed, and marketed as a new chip. The industry sells recycled or reconditioned ICs for several reasons, including: **1) Cost:** Recycled ICs can be sold at a lower price than new, original ones because they are not manufactured from scratch. **2)Availability:** In some cases, original ICs may not be readily available due to limited production runs or discontinued products. Recycled ICs can provide an alternative source for those looking to obtain a particular part. **3) Quality control concerns:** While some companies have rigorous quality control processes for refurbished ICs, not all do. This can lead to concerns about the quality and reliability of the parts. Overall, recycled ICs harm the market by decreasing the quality and reliability of products, hurting brand reputation, and disrupting the flow of investment into innovation. Not only that but it is difficult to make sure that the recycled components are genuine and of the quality that they are marketed as. Therefore, ensuring the reliability, quality, security, and integrity of electronic devices and systems depends heavily on the capacity to detect recycled ICs. It is imperative to develop methods for detecting them to ensure the reliability and safety of devices and systems, but they pose a unique challenge as they are often difficult to detect because they appear to be functional and often have the same markings as legitimate components. Many electronics industries continue to have difficulties in the identification process. Thus, the detection of recycled ICs remains a serious issue, and the industry is continuously working on improving the methods to make them more reliable and effective. In this paper, we will discuss the numerous ways that an individual can effectively detect the existence of a recycled IC.

II. TECHNIQUES

Physical inspections: Typically, recycled integrated circuits resemble the devices they are designed to replicate in terms of look, operation, and markings but they were utilized for a while before they were put back on the market. Even the best physical inspection methods won't be able to positively identify them because effective detection relies heavily on the expertise of the inspector, the design of every IC, and the specialized equipment. Physical inspection techniques include:

1) Incoming inspection: This is the first group of physical inspections. It consists of techniques such as **visual inspection**, and **X-ray imaging**. The latter is a technique where the rays enter the component and create a 2D image of its internal layers which can be analyzed for signs of damage, tampering, or counterfeiting. This technology thus be used to verify the authenticity of an IC by comparing the internal structure to a known good reference.

2) Exterior test: This is the second group of techniques to identify recycled ICs. Exterior tests are being conducted to analyze the leads and package's exterior of the IC. This group of tests consists of methods like **Package configuration and dimension analysis**, where the physical dimensions of the ICs are measured using either handheld or automated test equipment in package configuration and dimension analysis. Any abnormal measurement difference from the specification sheet suggests that the IC might be fake. **Blacktopping testing**, where a short circuit is applied between two adjacent metal lines in an IC, using a conductive material, such as metal or carbon. The short circuit produced by the blacktopping procedure can be utilized to identify changes in the device's electrical properties that can signify recycling, because a recycled IC may have different electrical characteristics from the original device due to changes in its material properties or manufacturing process. However, it’s important to notice that blacktopping is a destructive testing method, meaning that the IC will be damaged or destroyed during the process. **Microblasting analysis**, where the surface of the IC is bombarded with a variety of blasting agents with the appropriate grain sizes, and the materials are collected for examination. Glass beads, sodium bicarbonate powder, aluminum oxide powder, and other materials are frequently used as blasting agents**.** **Hermiticity testing**, which measures the degree of symmetry of the IC's electromagnetic fields. This can indicate if it has been altered or recycled. The test uses a variety of electromagnetic measurement techniques, including frequency and time domain analysis, to determine the hermiticity of the IC. A failure of the hermiticity test indicates IC is tampered with or counterfeit thus it’s a good indication that it has been recycled. **Scanning Electron Microscopy (SEM)**, where a focused beam of electrons is scanned over the surface of the IC, and the electrons that are emitted from the surface are collected and used to generate a high-resolution image of the surface's structure. So, SEM is used to verify the authenticity of the IC by examining its surface structure. If the surface structure appears different than the original IC's surface structure, then probably the IC is associated with the recycling process. Lastly, there is **Scanning Acoustic Microscopy (SAM)** that is a technique similar to SEM, but acoustic waves are used instead of electrons. They are transmitted into the IC, and the reflections of the wave are used to generate an image of the internal structure of the device. SAM can be used to examine the thickness or uniformity of the metal lines on the IC and any variations that might exist will suggest that the device has been disassembled and reassembled with new components, thus it has probably been recycled . In this point it is important to point out that SAM is one of the most effective, but priciest, methods of understanding the structure of an IC.

3) Interior Test: In this third group, delid or decapsulation is used to inspect the IC's internal architecture, including its die and bond wires. Three widely used techniques are commercially available for decapsulation. These are chemical, mechanical, or laser-based. Chemical decapsulation includes using an acid solution to erode the packaging, recent laser-based methods can effectively remove portion of the package, and mechanical decapsulation entails grinding the component till the die is visible. The following tests can be carried out after the IC has been decapsulated and the necessary structures have been made visible: **Optical inspection**, where the physical characteristics of the IC are visually examined. The test involves using high-resolution microscopy to inspect the surface features of the IC, such as wire bonding pads, metal lines, and other physical characteristics. The inspector looks for signs of tampering, such as scratches, discoloration, or other physical damage, which may indicate that the IC has been recycled or refurbished. **Wire pull**, which is used to evaluate the strength of the connections with the die. If the IC is used over time, the adhesiveness between the die and bond wires deteriorates. So, it can be determined whether an IC is recycled or not by testing the pulling force with the original components. **Die shear**, where the physical integrity of the die is examined. The die is the silicon substrate that contains the transistors and other components of the IC. The test involves mechanically shearing, or cutting, the die from the package, and then inspecting the cut surface for signs of reuse, such as evidence of previous bonding or cracks. Die shear, however, is a destructive test, meaning that the IC can no longer be used after the procedure, but it is a highly reliable method for detecting recycled ICs. It is important to point out that die shear can be performed only in hermitic devices. **Ball shear**, where the bond connections between an IC and its package are tested. The test involves applying a mechanical force to the bonding wire that connects the IC die to the package and measuring the force required to break the bond. The test provides information about the strength and reliability of the bond and can be used to detect recycled or refurbished ICs. In a recycled or refurbished one, the bond connections may have been damaged or weakened, leading to a lower ball shear strength compared to a new IC. Ball shear testing in general is a non-destructive test and can be performed on individual or a batch of ICs, making it a useful tool for quality control in the electronics manufacturing industry. Finally, **SEM** or **SAM** where they are analyzed in the previous paragraph, can be used to identify the interior, and can point out recycled or refurbished ICs.

4) **Material Analysis:** This technique is used to confirm the IC's chemical consistency. This is the only type of testing that can identify flaws and material-related anomalies. The methods employed in this category are **X-ray fluorescence (XRF),** which is used to find a material's elemental composition. It functions by exposing the sample to X-ray radiation, which excites the electrons within the sample's atoms and causes them to generate secondary X-rays with various energies. These energies can be used to identify the elements that are present in the sample. Therefore, this method can be used to check the makeup of the elements in the component and can distinguish between original and refurbished ICs. If, for instance, it detects lead or other potentially dangerous substances in the component it probable means it's tampered with or recycled. **Fourier Transform Infrared (FTIR) spectroscopy,** where it operates by shining infrared light on the sample, then observing the spectrum of emission or absorption bands that results. These bands can be utilized to discriminate between various materials and to pinpoint the chemical functional groups that are present in the sample. Thus, it can be used to verify the composition of the sample or detect the existence of elements that indicates recycling processing. **Ion chromatography** which is used to separate and quantify the ions present in a sample. It can be used to find impurities or contaminants that might have an adverse effect on the functionality or dependability of the components. It works by passing a sample through a column filled with a specific ion exchange resin, which separates the ions based on their charge and size. The separated ions are then detected and quantified using an electrode or a detector. For example, if it detects the presence of heavy metals or other hazardous materials it means that the IC probably has been through recycling process. **Raman spectroscopy** where the chemical composition of a sample is identified and examined using a method like FTIR. It can be used to verify the authenticity of the components and detect any potential defects or contaminants. t computes the dispersed light produced after a sample is laser-illuminated. The change in energy of the scattered light, which is an indication of the chemical functional groups present, can be used to identify the molecular vibrations in the sample. Essentially, it detects the presence of any contaminants in the sample, and the existence of those could be an indication of refurbishing. Finally, **Energy Dispersive Spectroscopy (EDS)**, just like the other spectroscopies ,is used to acknowledge the elemental makeup of a sample. It operates by exposing the sample to X-rays and determining how much energy is released in the form of X-ray fluorescence. The elements in the sample may be identified and their relative abundances can be calculated using the energy of the fluorescence, which is typical of the components in the sample, thus distinguishing recycled from original ICs.

<u>Electrical inspections</u>: It involves evaluating the recycled ICs' electrical properties and performance to make sure they adhere to industry standards and regulations.

Essentially, measurements in electrical parameters such as power consumption current ,voltage, capacitance, functional tests in memory or in the microprocessor, burn-in and structural tests are conducted to verify the reliability of the IC. It consists of more valid techniques than physical inspection because actual measurements of the characteristics are taken and can be compared with them from original ICs to distinguish recycled from untouched ones. It must be pointed out that for some of these tests, an automatic test equipment (ATE) may be needed. Electrical inspection techniques include:

1) Parametric Tests: It contains methods that measure the parameters of the IC. The DC and AC values may deviate from their specified if the chip has previously been utilized. One can determine whether a component is fake or not by looking at the test results from a parametric test. They are separated in DC and AC parametric tests.

- **I.** **DC:** In DC there are numerous methods of parametric testing such as **contact test,** where it entails physically probing an IC's pins or pads to find its electrical properties, such as voltage levels, capacitance, and resistance. The result from the test can determine whether the IC is original or whether it was recycled from another device. **Power consumption test**, where it analyzes the amount of power an IC uses while operating and contrasts it with the IC's predicted power consumption. If the power consumption differs noticeably from the anticipated value, it could mean that the IC has been recycled. **Leakage test,** where it involves measuring the electrical current that is flowing between an IC's various terminals when it is off (or in a "low power" state). If there is leakage current, it is a sign that the IC was reused in another device. **Output short current test**, where in order to perform the test, an IC must be shorted to ground, which is an abnormal working situation. The current that passes through the output pins of the IC must be measured in this condition. To determine whether an IC is original or recycled, the output short current is compared to the values that are typical for that IC. **Output drive current test** is like the output short current test, but the test is conducted under normal conditions instead of abnormal, and finally there is the **threshold test,** where the test entails determining the voltage values at which an IC flips between its low and high output states. To identify if an IC is original or recycled, the threshold levels are compared to the expected values for that specific IC. It may be a hint that the IC was recycled from another device if the threshold levels are significantly different from the predicted values.
- II. **AC:** Here the tests involve the measurement of AC parameters at a specified range of frequencies. The following groups comprise AC parametric tests: **Propagation delay test**, where it calculates the propagation delay of a signal from an IC's input to output and compares it to the propagation delay that is typical of that IC to determine if it has been recycled or not. **Set up / hold time test**, where the test examines the time interval during which the input

signal to an IC must be stable (the "setup time") and the time interval after the setup time during which the input signal must remain stable (the "hold time"). When these timing characteristics are compared to the predicted values for a specific IC, it may be determined if it is original or recycled. **Access time test**, where is a method to gauge how fast memory is in ICs. The test examines the amount of time it takes an IC to access a certain memory location and retrieve the data that is there. As it affects the overall speed and effectiveness of the system in which they are employed, this is a crucial performance characteristic for memory ICs. It is possible to tell whether a memory IC is original or recycled by comparing the access time to the predicted values for that original memory IC. Finally, the **rise/fall time test** is a technique for evaluating how well digital ICs operate in electronic devices. The test calculates the rise time (time it takes for an output signal to go from a low to a high state) or the fall time (time it takes for a signal to go from a high to a low state). Those times are compared with the expected values of digital IC to determine if it is original or recycled.

2) Functional Test: They are the most effective method of ensuring a component's functionality because most of the defect ICs, including recycled ones, can be detected during this test. There are three major types of functional test. **Function verification**, where it is verified whether a component functions properly. It establishes if individual parts, which may be created using various technologies, work together cohesively and generate the desired outcome. **Memory test**, where read and write operations are issued to the memory of the IC, to check if it functions correctly. Also, **MARCH test** is conducted to detect defect ICs. The IC is put through a variety of test patterns to look for faults that could impair the performance or dependability of the IC, like short circuits or open circuits. Last but not least, **the functional Fmax analysis** method is used to determine he maximum operating frequency of digital ICs. The analysis is testing the IC at various frequencies, seeing how the output signals behave, and figuring out the highest frequency at which the IC still functions properly. As it affects the overall speed and effectiveness of the system in which they are utilized, the functional Fmax is a crucial performance metric for digital ICs. To evaluate if a specific digital IC is original or recycled, the functional Fmax is compared to the predicted values for that digital IC.

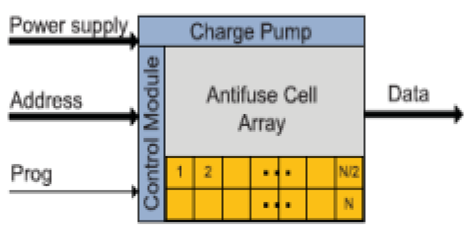
3) Burn-in tests: Burn-in is primarily responsible for ensuring a device's dependability. In order to discover infant mortality failures and unexpected failures and to ensure reliability, the device is operated at a high temperature to imitate a stress environment. The use of burn-in is crucial since it may quickly identify components labeled as military grade but actually being commercial grade. Additionally, it can get rid of components that are defective, including recycled ones, or components that weren't intended to function under such stress.

4) Structural Tests: These tests work well because they are capable of identifying some aging-related delays or faults in counterfeit and recycled ICs. They consist of **stuck-at fault tests,** which is a method of testing Integrated Circuits (ICs) for manufacturing defects. The IC is subjected to certain inputs throughout the test, and the output is examined to see if it corresponds to expectations. A "stuck-at" fault, in which a transistor in the IC is trapped in either the "0" or "1" state, is indicated by an output that differs from what is anticipated. Because recycled ICs may have undergone degradation or damage during the recycling process, which results in "stuck-at" faults, this test can be used to identify them. **Transition delay fault tests**, which is a technique for checking whether a digital component has flaws that could prevent it from switching between two logical states. During the test, the circuit is subjected to specified input patterns, and the amount of time it takes for the output to change states is time-stamped. A transition delay problem is present if the output does not switch when it should and it could mean that the component has been through tampering or recycling. Finally, **path delay fault tests,** which is a way to test digital circuits for flaws that affect signal propagation through the circuit. To perform the test, a circuit is subjected to a set of input patterns, and the circuit's response time is measured as a function of time. The presence of a path delay fault is indicated if the signal's travel time is longer than anticipated, which is a good indication that the component is counterfeit or reused.

<u>On-chip sensor:</u> it is suggested that a small on-chip sensor is placed inside the IC to distinguish between used and original ones. By analyzing statistical data, it is possible to differentiate between the aging that occurs in the field when the sensors are employed in ICs and the impacts of process and temperature fluctuations on them. Two main lightweight on-chip sensor are proposed in this paper:

I. **RO-Based Sensor**: A reference RO(RRO) and a stressed RO(SRO) generally make up the RO-based sensor. High threshold voltage (HVT) gates are utilized in the SRO's design to speed up aging so that used ICs may be recognized. Since the RRO is gated off from the power supply while the chip is operating, it is not under as much stress. The usage period of the test chip may be shown by the frequency difference between the two of them in the IC. Along with the RRO and SRO, a control module, a multiplexer, a timer, and a counter make up the rest of the sensor. The counter, which is controlled by the timer, counts the number of cycles produced by the two ROs within a given period of time. The timer uses the system clock to reduce measurement period fluctuations brought on by circuit aging. The multiplexer, which is managed by the ROSEL signal, chooses which RO will be monitored. Both ROs are similar and are made up of HVT components. Three modes, which are managed by the mode signal, are used by both: 1) While the IC is in **manufacturing test mode**, both ROs will be cut off from the power supply and won't age. Depending on the IC's test methods, this mode only lasts a brief period of time. 2) When the IC is in **normal functional mode**, the SRO is gated on and ages while RRO is unplugged from VDD and VSS. While the RRO's frequency won't significantly change, the SRO's frequency will decrease. ICs primarily operate in this mode. 3) When the IC is in authentication mode (that is, when an IC is removed off the market and its authenticity is to be checked), both will be gated on by connecting to the power source. The ROSEL signal will choose which RO to measure, and the timer and counter will be turned on to count the number of cycles for each RO. Mode signals would disable the rest of the IC's capabilities, and the authentication process only requires a brief amount of time. Since the chip has been operating in its normal functional mode for a considerable amount of time in a recycled IC, the SRO will have gotten older due to its own oscillation. Thus, because it is gated off, the RRO won't have aged as much and can efficiently demonstrate the IC's aging. However, in this implementation the RROs' and SROs' inverters are physically near to one another in the sensor to lessen the effect of intra-die process fluctuations. So, it might still be challenging to totally rule out the sensor's exposure to fluctuations in the inter die process. Additionally, this sensor merely approximates the usage duration as an indicator of aging in the SRO. As a result, this sensor's sensitivity (the least time at which recycled ICs can be recognized by sensors) is constrained. For instance, it might not be able to detect recycled ICs used for less than a month.

II. **AF-Based Sensor:** To give a more precise usage duration, and to find recycled ICs that are only utilized for a very brief period, the AF-based sensor is proposed. The main difference from the RO sensor is the usage of AF memory block. It is a block of memory that is one-time programmable (OTP), meaning that recycling processes could not remove its' content. The usage time, measured by the counters of the sensor, is saved dynamically there. It has the following characteristics: 1) Compared to other types of OTP structures, it requires less power to program or read. 2) An AF's area is considerably smaller than that of an efuse, and 3) its construction does not necessitate any additional masking or manufacturing handling processes. Below a typical block is shown:



Essentially, two metal lines (electrodes) are the building blocks of a memory cell, and they are separated by a thin insulating layer. When high voltage is applied to the AF memory, the insulating layer breaks down, causing a permanent change in its electrical characteristics. The breakdown of the insulating material creates a low-resistance pathway between the two electrodes, effectively connecting them (closed state). A "0" and a "1" are represented by the open and closed states of this switch, respectively, which can be used to store binary data. Thus, AF-based sensors can used to detect recycled ICs by determining whether a memory cell has been programmed. The sensor gives the memory cells a test voltage and monitors the current passing through them. If there is a low current flow, the switch is likely to be open, meaning that the IC has not been programmed and therefore isn't recycled. If the switch is closed, it signifies a strong current flow, which means the IC has been programmed and hence is recycled.

III. REFERENCES

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