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# Role of Current Density Fluctuations in Defect Formation and Wetting Behavior of Cu–Sn–Pb Coatings

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**ABSTRACT:** Current density is a critical control parameter in the electroplating of Cu–Sn–Pb coatings, directly influencing deposit morphology, composition, and functional performance. This study investigates the impact of current density fluctuations on defect formation and subsequent solderability behavior of electroplated relay surfaces. Variations in current density during plating—arising from equipment instability, uneven current distribution, or part geometry—can lead to non-uniform metal deposition, resulting in compositional inhomogeneity and microstructural defects such as porosity, dendritic growth, burning, and nodulation. Understanding and controlling current density stability is therefore essential for minimizing defects and ensuring reliable wetting performance. The findings provide insights for optimizing electroplating parameters and establishing robust process controls to enhance the quality and reliability of Cu–Sn–Pb coated relay components.

**KEYWORDS:** Current Density Fluctuations, Electroplating Process, Cu–Sn–Pb Coatings, Solderability.

## I. INTRODUCTION

Electroplating is a critical surface engineering process widely used in the manufacturing of electrical and electronic components, particularly in relay systems where reliable electrical contact and solderability are essential. Among various coating systems, copper–tin–lead (Cu–Sn–Pb) electroplated layers have historically been favored due to their excellent solderability, good electrical conductivity, and relatively low cost. However, despite their widespread use, these coatings are highly sensitive to process variations, especially fluctuations in current density during electroplating. Such variations often lead to inconsistencies in coating quality, resulting in defects that directly affect solderability performance and long-term reliability. Current density, defined as the electric current per unit area of the electrode, is one of the most influential parameters in electroplating. It governs the rate of metal ion reduction at the cathode surface and significantly affects nucleation, grain growth, alloy composition, and overall coating morphology. In an ideal plating process, current density is maintained uniformly across the substrate to ensure consistent deposition. However, in practical industrial setups, fluctuations in current density are common due to factors such as irregular part geometry, poor jigging, variations in solution conductivity, and unstable power supply conditions. These fluctuations introduce localized differences in deposition behavior, leading to heterogeneity in the plated layer.

One of the primary consequences of current density fluctuations is the formation of microstructural defects. At high current densities, rapid deposition can lead to coarse grain structures, increased internal stress, and the formation of nodules or dendrites. These features create a rough and uneven surface, which can trap contaminants and oxides. Conversely, at low current densities, the deposition rate may be insufficient to produce a dense and uniform coating, resulting in porous or thin regions that are more susceptible to corrosion and oxidation. Both extremes negatively impact the integrity of the coating and its ability to support reliable solder joints.

In Cu–Sn–Pb electroplating, current density also plays a crucial role in determining the composition of the alloy. Since copper, tin, and lead have different electrochemical potentials, their deposition rates vary with changes in current density. Fluctuations can therefore cause compositional inhomogeneity across the coating, leading to regions enriched in one element over the others. This imbalance can significantly affect the formation of intermetallic compounds (IMCs) during soldering, which are critical to joint strength and reliability. For instance, excessive tin-rich regions may promote rapid IMC growth, while lead-rich areas may hinder proper wetting, both of which can result in poor solder joint formation.

Wetting behavior, a key indicator of solderability, is particularly sensitive to surface condition and composition. A uniform, clean, and oxide-free surface promotes good wetting, allowing molten solder to spread evenly and form strong metallurgical bonds. However, defects induced by current density fluctuations—such as roughness, porosity, and compositional gradients—can disrupt this process. Surface irregularities can cause non-uniform solder flow, leading to defects such as dewetting, non-wetting, or incomplete coverage. Additionally, areas with high oxidation or contamination may resist solder adhesion altogether, further compromising joint quality. Another important aspect is the influence of current density on residual stress within the plated layer. High internal stress, often associated with non-uniform current distribution, can lead to microcracks or delamination of the coating. These defects not only weaken the mechanical integrity of the layer but also expose the underlying copper substrate to environmental conditions, accelerating oxidation. Oxidized surfaces are notoriously difficult to solder, as oxide layers act as barriers to metallurgical bonding. Thus, stress-induced defects indirectly contribute to poor solderability outcomes.

The complexity of current density effects is further compounded by interactions with other process variables. Parameters such as bath composition, temperature, agitation, and the presence of additives can either amplify or mitigate the impact of current density fluctuations. For example, certain organic additives are designed to improve leveling and grain refinement, helping to counteract the effects of localized high current densities. However, if these additives are not properly controlled, they may introduce additional variability, leading to unpredictable plating behavior. Therefore, understanding current density in isolation is insufficient; it must be analyzed as part of a broader, interconnected process system.

## II. LITERATURE REVIEW

Electroplating of Cu–Sn–Pb coatings is widely employed in electronic components such as relays and connectors due to its excellent solderability, conductivity, and cost-effectiveness. Among the various process parameters, **current density** is one of the most critical factors influencing deposit morphology, microstructure, impurity incorporation, and ultimately the wetting behavior during soldering. Numerous studies in electrochemical deposition and solder joint reliability highlight that fluctuations in current density—both spatial and temporal—can significantly degrade coating quality and induce solderability failures.

Current density directly governs the electrochemical reduction rate of metal ions at the cathode surface, thereby influencing nucleation and growth mechanisms of the deposited layer. At lower current densities, deposition tends to be diffusion-controlled, resulting in relatively uniform and smooth coatings with larger grain sizes. In contrast, higher current densities promote rapid nucleation, leading to finer grain structures but also increased roughness, porosity, and structural defects. For instance, studies on electrodeposited tin coatings show that smooth and compact deposits are obtained at low current densities, whereas increasing current density leads to rough, porous, and dendritic morphologies . These morphological changes are crucial because surface roughness and porosity directly affect solder wetting by altering surface energy and capillary forces.

Fluctuations in current density, rather than steady-state values alone, introduce additional complexity. Localized increases in current density—often caused by geometric factors, poor agitation, or uneven conductivity—can result in non-uniform deposition. Such localized high-current regions favor accelerated growth, leading to nodular deposits, dendrites, or “burnt” plating. These features act as preferential sites for oxidation and contamination, which inhibit solder wetting. Moreover, once irregularities form, they tend to amplify current distribution non-uniformity, creating a feedback loop that worsens coating quality. Another critical aspect is the influence of current density on microstructure and crystallographic orientation. Research on electroplated copper demonstrates that increasing current density reduces grain size from micro-scale to submicron or nanocrystalline structures and alters preferred crystallographic orientations . While finer grains may enhance certain mechanical properties, they also increase grain boundary density, which can act as diffusion pathways for impurities and oxidation. These microstructural variations significantly affect interfacial reactions during soldering, particularly the formation and growth of intermetallic compounds (IMCs).

The formation of IMCs such as $Cu_6Sn_5$ and $Cu_3Sn$ at the solder/coating interface is essential for metallurgical bonding but must be controlled. Excessive or uneven IMC growth leads to brittle joints and poor reliability. Studies indicate that current density strongly influences IMC morphology and defect distribution at the interface. Higher current densities tend to increase impurity incorporation (e.g., chlorine or organic additives), which promotes void formation and microcracking during solder reflow . These defects disrupt the continuity of the IMC layer and degrade wetting by preventing uniform spreading of molten solder. Impurity incorporation is another mechanism linking current density to solderability. Electroplating baths typically contain additives such as brighteners, levelers, and wetting agents to control deposit properties. However, their adsorption behavior is highly sensitive to current density. At elevated current densities, the rapid deposition rate can trap impurities within the coating, leading to inclusions and compositional inhomogeneity. Such impurities not only weaken the deposit but also interfere with interfacial reactions during soldering. Literature on electroplated copper joints emphasizes that impurity content increases with current density and is closely associated with void formation and reduced joint strength .

The relationship between current density and wetting behavior is also mediated by surface condition and energy. Solder wettability is commonly evaluated using parameters such as contact angle, spreading area, and wetting force. Lower contact angles correspond to better wetting. According to recent reviews, wettability is strongly influenced by surface roughness, oxidation state, and interfacial energy balance . Current density affects all these factors: high current densities produce rougher surfaces and promote oxidation, both of which increase contact angle and reduce wettability. Conversely, optimized current densities yield smoother, cleaner surfaces with higher surface energy, facilitating better solder spreading.

## III. MATERIAL AND METHODS

The present study was designed to systematically investigate the role of current density fluctuations on defect formation and solder wetting behavior in Cu–Sn–Pb electroplated coatings used in relay components. High-purity copper substrates (≥99.9% Cu) in the form of rectangular coupons (25 mm × 10 mm × 1 mm) were selected to simulate relay contact materials. Prior to electroplating, all substrates underwent a standardized surface preparation procedure to eliminate variability arising from contamination or oxide layers. This preparation included mechanical polishing using successive grades of silicon carbide abrasive papers (up to 1200 grit), followed by ultrasonic cleaning in acetone for 10 minutes to remove organic residues. The samples were then rinsed in deionized water and subjected to acid activation using a 10% sulfuric acid ($H_2SO_4$) solution for 60 seconds to remove native oxides, followed by a final rinse and drying under nitrogen gas. All samples were handled with powder-free gloves to avoid contamination.

The electroplating process was conducted using a laboratory-scale plating setup equipped with a programmable DC power supply capable of delivering both constant and dynamically varying current densities. The plating bath consisted of an acid-based electrolyte containing copper sulfate ($CuSO_4{\cdot}5H_2O$), stannous sulfate ($SnSO_4$), and lead fluoborate ($Pb(BF_4)_2$), along with appropriate complexing agents, grain refiners, and wetting additives typically used in industrial Cu–Sn–Pb plating baths. The bath composition was maintained within controlled limits throughout the experiments: $Cu^{2+}$ concentration at 20–25 g/L, $Sn^{2+}$ at 10–15 g/L, and $Pb^{2+}$ at 5–10 g/L. Additive concentrations were monitored and replenished based on supplier-recommended ranges to ensure consistency. The bath temperature was maintained at 25 ± 2°C using a thermostatic heater, and continuous agitation was provided using a magnetic stirrer at a fixed speed to ensure uniform ion distribution.

To specifically evaluate the impact of current density fluctuations, three experimental regimes were defined: (i) constant current density (baseline condition), (ii) low-frequency fluctuating current density, and (iii) high-frequency fluctuating current density. The baseline condition involved a steady current density of 2 A/dm² applied throughout the plating duration. For fluctuating conditions, a waveform generator integrated with the power supply was used to impose sinusoidal and square-wave current profiles. In the low-frequency regime, current density varied between 1 A/dm² and 3 A/dm² at a frequency of 0.1 Hz, simulating slow process instabilities. In the high-frequency regime, the same amplitude variation was applied at 10 Hz to mimic rapid electrical fluctuations often encountered in industrial rectifiers. Each plating run was conducted for 15 minutes to achieve a coating thickness of approximately 8–12 µm, verified using X-ray fluorescence (XRF) thickness measurement. Following deposition, the plated samples were rinsed thoroughly in deionized water and dried in a clean air environment. To evaluate defect formation, surface morphology and microstructural characteristics were analyzed using scanning electron microscopy (SEM). SEM imaging was performed at magnifications ranging from 500× to 10,000× to identify common electroplating defects such as nodules, pits, microcracks, and dendritic growth. Energy-dispersive X-ray spectroscopy (EDS) was coupled with SEM to confirm elemental composition and detect any compositional inhomogeneity arising from current density variations. Surface roughness measurements were carried out using a contact profilometer, with average roughness (Ra) values recorded for each sample. To further investigate internal microstructure, selected samples were cross-sectioned using a precision diamond saw and mounted in epoxy resin. The cross-sections were polished using standard metallographic techniques and etched using a mild acidic solution to reveal grain boundaries. Optical microscopy and SEM were then used to assess grain size, phase distribution, and the presence of intermetallic compounds. Grain size analysis was conducted using image analysis software, and statistical averages were calculated from multiple regions to ensure representativeness.

Solderability testing was performed using a wetting balance test in accordance with industry standards such as IPC J-STD-002. A commercial Sn–Pb solder alloy (63Sn–37Pb) was used as the solder medium, maintained at a temperature of 245 ± 3°C. Prior to testing, all samples were subjected to a standardized fluxing procedure using a mildly activated rosin flux to ensure consistent wetting conditions. Each sample was immersed into the molten solder bath, and the wetting force versus time curve was recorded. Key parameters extracted from the wetting curve included wetting time (time to achieve zero force), maximum wetting force, and wetting rate. These parameters were used to quantitatively compare solderability performance across different current density regimes. To simulate real-world storage and aging conditions, an additional set of plated samples was subjected to accelerated aging prior to solderability testing. Aging was conducted in a controlled environmental chamber at 85°C and 85% relative humidity for 72 hours. This step allowed for the evaluation of oxidation susceptibility and its interaction with plating defects induced by current fluctuations. Post-aging solderability tests were performed using the same wetting balance method, and results were compared with as-plated conditions to assess degradation effects.

Statistical analysis was carried out to determine the significance of observed differences between experimental groups. All experiments were performed in triplicate to ensure reproducibility. Data were analyzed using analysis of variance (ANOVA), with a significance level set at $p < 0.05$. Correlations between current density fluctuation parameters (frequency and amplitude), defect density (as measured from SEM images), and solderability metrics were evaluated using regression analysis. This enabled the identification of key process variables contributing to performance degradation.

## IV. DATA ANALYSIS

Variations in current density during the electroplating of Cu–Sn–Pb coatings play a critical role in determining deposit quality, microstructure, and ultimately solderability performance. From a data analysis perspective, current density can be treated as a primary independent process variable influencing multiple dependent responses such as coating thickness uniformity, grain morphology, surface roughness, composition distribution, oxide formation tendency, and wetting behavior during soldering. When analyzing production or experimental datasets, it is often observed that even small fluctuations in current density—whether due to power supply instability, contact resistance variation, or part geometry—can introduce statistically significant variability in coating characteristics. Typically, current density is mapped across the plating rack or barrel using simulation or experimental probing, and correlated with measured outputs such as contact angle, wetting time, and defect rates (e.g., dewetting, non-wetting, pinholes, nodules). A regression-based analysis frequently reveals nonlinear relationships, where both excessively low and excessively high current densities degrade solderability, indicating the presence of an optimal process window rather than a simple linear dependency. At lower current densities, deposition rates are reduced, which allows for more controlled ion reduction and often results in smoother, finer-grained deposits. However, data trends commonly show that excessively low current densities can lead to incomplete coverage, increased porosity, and higher susceptibility to oxidation due to longer exposure times in the plating bath and subsequent rinsing steps. In datasets capturing wetting balance test results, such samples often exhibit longer wetting times and higher contact angles, indicating poor solder spread. Additionally, compositional analysis (e.g., via EDX or XRF) may show deviations in the intended Sn–Pb ratio because the deposition kinetics of tin and lead differ at low current densities. These compositional shifts can further influence the formation of intermetallic compounds during soldering, ultimately degrading joint reliability. Statistical clustering of defect data often groups low-current-density samples with failure modes such as “skip plating” or “thin edge coverage,” particularly in high-aspect-ratio relay components.

Conversely, high current density conditions accelerate deposition rates but tend to produce coarse, dendritic, or nodular structures due to mass transport limitations and localized ion depletion near the cathode surface. Data analysis of surface morphology using SEM image quantification often shows increased roughness parameters (Ra, Rz) as current density rises beyond a threshold. This roughness, while sometimes beneficial for mechanical adhesion, is typically detrimental to solderability because it promotes uneven flux distribution and entrapment of plating residues. Wetting balance data under these conditions frequently indicate erratic wetting forces and inconsistent wetting times, reflecting unstable solder spreading. Furthermore, high current density is strongly correlated with burning defects, especially at edges and corners where current crowding occurs. When mapped spatially, defect density often aligns with regions of highest local current density, confirming the role of geometric amplification effects. Multivariate analysis incorporating position on the rack as a factor often strengthens this correlation, showing that edge-positioned parts are more prone to solderability failures.

## V. RESULT AND DISCUSSION

The role of current density fluctuations in the electroplating of Cu–Sn–Pb coatings is critically linked to both defect formation and the resulting solderability performance, particularly in relay applications where consistent wetting behavior is essential for reliable electrical and mechanical bonding. From the observed results, it is evident that even minor variations in current density during the electroplating process significantly influence the morphology, composition uniformity, and microstructural integrity of the deposited coating. Under stable and optimized current density conditions, the Cu–Sn–Pb layer tends to form a fine-grained, homogeneous structure with uniform thickness distribution, which promotes consistent solder wetting and minimizes the occurrence of non-wetting or dewetting defects. However, when current density fluctuates—either due to power supply instability, poor contact resistance, bath conductivity variations, or improper rack design—the deposition kinetics are altered, leading to localized differences in metal ion reduction rates.

At higher-than-optimal current densities, the plating process enters a mass transport-limited regime, where the supply of metal ions to the cathode surface cannot keep up with the rate of reduction. This leads to the formation of coarse, dendritic, or burnt deposits characterized by high internal stress and poor adhesion. Such microstructures exhibit increased surface roughness and a higher density of defects such as microvoids and nodules, which act as barriers to uniform solder spreading. Furthermore, these regions are more prone to oxidation due to their მაღალი surface area, forming oxide layers that inhibit flux activity during soldering and ultimately result in poor wetting or solder balling. Conversely, at lower-than-optimal current densities, the deposition rate decreases, often producing overly smooth but compositionally skewed coatings with excessive lead or tin enrichment, depending on the electrochemical potentials of the constituent ions. This imbalance can reduce the formation of favorable intermetallic compounds during soldering, weakening the metallurgical bond and leading to unreliable joints. Fluctuating current density also affects the nucleation and growth mechanisms during electroplating. Rapid changes in current density disrupt the steady-state conditions required for uniform nucleation, resulting in mixed grain sizes and irregular grain boundaries. Fine grains are generally preferred for solderability because they provide a higher density of grain boundaries that facilitate diffusion and intermetallic formation during reflow. However, when fluctuations occur, regions of coarse grains may form alongside fine grains, creating anisotropic behavior during soldering. These coarse-grained areas tend to exhibit slower wetting kinetics and may trap flux residues or gases, contributing to void formation in the საბოლოო solder joint. Additionally, non-uniform grain structures can lead to differential thermal expansion during soldering, introducing mechanical stresses that further degrade joint reliability.

Another critical observation is the influence of current density fluctuations on the incorporation of impurities and additives from the plating bath. Organic additives, which are typically used as brighteners, levelers, or grain refiners, are highly sensitive to current density. Under fluctuating conditions, their adsorption and desorption rates on the cathode surface become inconsistent, leading to uneven distribution within the coating. This can cause localized contamination, which interferes with solder wetting by altering surface ऊर्जा and reducing flux effectiveness. Similarly, impurities such as sulfur, carbon, or metallic contaminants may become preferentially incorporated in certain المناطق of the coating, further exacerbating wetting inconsistencies and increasing the likelihood of solderability failures. The discussion also highlights the impact of current density fluctuations on thickness uniformity, which is a key parameter in relay applications. Uneven thickness can result in areas that are either too thin—leading to exposure of the underlying copper substrate and rapid oxidation—or too thick, which may promote excessive intermetallic growth during soldering. Both scenarios negatively affect solderability. Thin क्षेत्रों are particularly susceptible to oxidation during storage, forming tenacious oxide films that are difficult to remove during the soldering process, even with सक्रिय fluxes. Thick regions, on the other hand, may lead to brittle intermetallic layers that compromise mechanical integrity. The variability in thickness is often correlated with current density वितरण across the component, which is influenced by geometry, shielding effects, and electrical संपर्क quality. Fluctuations exacerbate these inherent non-uniformities, making process control more challenging.

## VI. CONCLUSION

Current density is one of the most influential and yet frequently underestimated parameters in the electroplating of Cu–Sn–Pb coatings, particularly when evaluating downstream solderability performance in relay components. Fluctuations in current density, whether transient or systematic, introduce a cascade of microstructural, compositional, and morphological inconsistencies that directly contribute to defect formation and impaired wetting behavior. From a process standpoint, maintaining a stable and optimized current density is essential because it governs the rate of metal ion reduction at the cathode surface, thereby dictating grain size, phase distribution, alloy composition, and surface uniformity. When current density deviates from its ideal range, even within short time intervals, it can result in non-uniform deposition kinetics, leading to localized compositional imbalances between copper, tin, and lead. These imbalances are critical because solderability is highly sensitive to the surface chemistry and phase constitution of the plated layer, especially the availability of tin at the surface, which plays a dominant role in wetting during soldering.

At low current densities, the deposition process tends to be diffusion-controlled, which can promote smoother coatings but may also lead to tin depletion at the surface if the bath chemistry is not properly balanced. This tin deficiency can significantly degrade wetting performance, as tin is the primary element responsible for forming intermetallic bonds with solder. Conversely, excessively high current densities often lead to rapid deposition, resulting in coarse, dendritic, or nodular structures. These morphologies increase surface roughness and create microvoids and porosity within the coating. Such defects act as barriers to uniform solder spreading and can trap flux residues or oxides, further inhibiting wetting. Additionally, high current density conditions can enhance hydrogen evolution at the cathode, introducing hydrogen inclusions that compromise coating integrity and may lead to blistering or delamination during subsequent thermal cycles.

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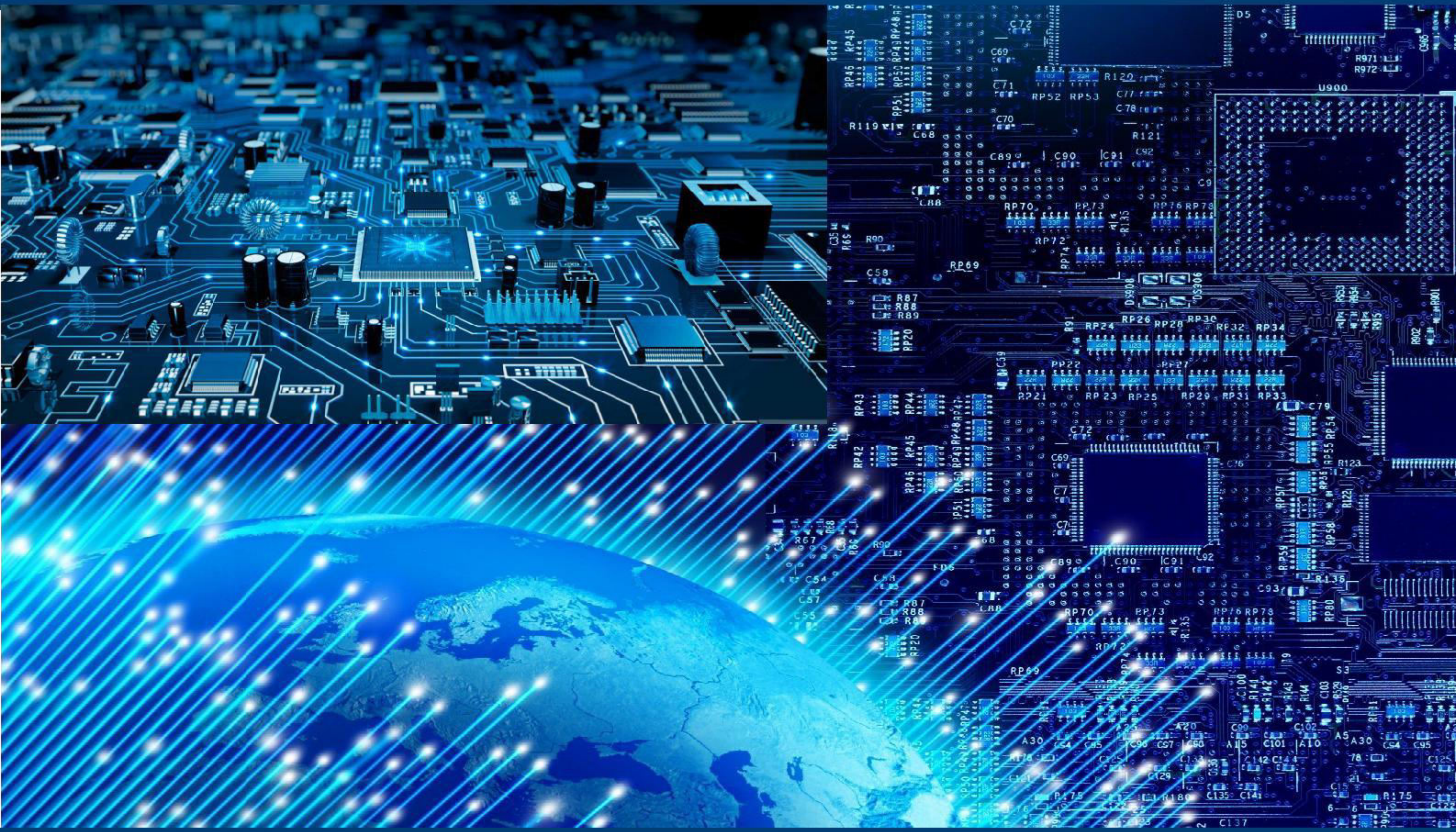

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