Review on Corrosion in Electronic Packaging Trends of Collaborative between Academia–Industry

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Abstract: This article reviews corrosion in electronic packaging mainly in the semiconductor industry over the world. The previous study was reviewed scientifically to highlight the significant work on corrosion in electronic packaging. A total of 467 and 762 studies were found in the IEEE Explore and Scopus databases from 2010 to 2020, respectively. After the search was limited to articles and proceedings, the databases showed only 319 from IEEE and 694 from Scopus. The keywords searching for this topic also emphasized corrosion wire bonding, corrosion leadframe, and corrosion solder. When searching for articles and proceedings were divided into three (3) categories such as academia, industry, and collaborative works, the database from collaborative works showed only 57 and 108 results in IEEE and Scopus, respectively. The studies were classified according to the process after some analysis using Microsoft Excel. Most of the previous studies were on corrosion in electronic packaging. From the study, we found that most of the journal articles were published by academia while the proceeding was published by industry. This information was extracted from IEEE Explore and Scopus databases. Since 2010, the trend of collaborative works among the industry and academia showed increased from 13 to 165 total publications in 2020. This review is significant to give an overview of the collaborative works between industry and academia on the corrosion issue in electronic packaging.

Keywords: corrosion; electronic package; wire bonding corrosion; solder corrosion; leadframe corrosion

1. Introduction

Corrosion is one of the domain knowledge areas which attract very much attention from both academia and industrial industry practice. Domain knowledge of corrosion involves the field of materials degradation. In industrial practice, corrosion becomes a very big issue that issue which effects the economic loses and reliability of the structure. Corrosion is very popular when subjected to metallic materials, for example in the iron and steel industry or product. It is very typical that iron and steel product experience rust on the surface due to their reaction to the environment. The ‘rust’ is a byproduct of the corrosion process. In metallic related industry, corrosion issues and behavior has been established, for example in the oil and gas industry, yet the research and development are still progressive significantly and initiates many areas of interest such as coating technology, corrosion protection, corrosion inhibitor, lowered corrosion rate via materials design and formulation, and to some extent on nanotechnology. This shows the huge interest in corrosion and corrosion-related area in metallic-related industries.

On the other hand, the electronic era has been introduced since the development of computers at large scale and tremendously increase many aspects of human wellbeing and technology. The electronics application started as assisting in technological development and changing human lifestyle and quality of life. The electronic also widens its application
across other sectors. Since electronics parts involve metallic materials as conductor, then the issue of corrosion also take place. However, this issue may not be serious as other industrial sectors and many electronics devices had a limited-time warranty service, for example, one or two years. However, current development sees that electronics usage and application has broadened across itself such as in medical, safety and security, manufacturing, transportation, telecommunication, etc. Until now, electronics devices and components also become more powerful, complex, and complicated. This is in line with technological development in electric and electronic (E&E), miniaturization, and multifunction.

Furthermore, in line with development in communication, sensors, and photonic technology, IoT, 5G, smart manufacturing, and robotic, allow electronic components and devices to be embedded in the application systems. This development may result in serious corrosion issues in electronics devices/components due to size factor from bulk scale and evolved to small scale up to fine pitch size, service-factor condition such as exposure to very high temperature and alternate with very cold temperature, exposure to the humid environment, extreme environment during services that may result in reliability and some cases leading to total catastrophic failure. The usage of electronic devices in automotive, aviation, and military need to ensure higher reliability during services. For example, electronic packaging in automotive. The automotive industry previously is the mechanical based industry that has evolved and transforms into electronic-based industry, for instance, all-electronic cars. So, reliability issues of electronic packaging or devices are very important to be addressed either in manufacturing, assembly, and in-service.

The corrosion issue in E&E is very important to raise. On the other hand, from the perspective of E&E, electronic packaging probably is the most responsible for the corrosion issue, since electronic packaging act as the brain of the system and consists of many different materials and different process technology in its assembly. One just imaging the very small copper wire that has been used as wire bonding to join the Cu leadframe and the silicon die is broken due to corrosion. This example alone is enough to highlight the important of corrosion issues in electronic packaging to be sought prior to service.

This review paper evaluates the scholarly activities regarding corrosion to map the interest of corrosion activity from the perspective of academia and industry. We hypothesize that scholarly work reported by academia reflects the fundamental interest while the industry is from practical interest. The issues raised by both industry and academia will be assessed accordingly. The chain of knowledge from fundamental to applications/commercialization. This involves many parties such as academia and industries. How research and development (R&D) from lab scale until product commercialization. We use two types of scientific search engine, Scopus and the Institute of Electrical and Electronics Engineers (IEEE) to evaluate and analyze scholarly activities such as journals and proceeding publications. IEEE is the world’s largest technical professional organization which is dedicated to advancing technology. It has more than 409,000 members from more than 160 countries over the world. It has 39 technical societies and seven technical councils representing a wide range of IEEE technical interests. It also has more than 5 million technical articles consisting of transactions, journals, conference papers, and magazines, and more than 1200 technology standards in the IEEE Xplore® digital library. While Scopus is a search engine that combines a comprehensive, expertly curated abstract and citation database with enriched data and linked scholarly literature across a wide variety of disciplines. Scopus has often been chosen by academic, business, and government institutions since 2004 with data coverage in advanced analytics and technology. It has published more than 82,000,000 documents from 1788, 1,700,000 cited references from 1970, 1,700,000 author profiles, 234,000 books, 7000 publishers, and 80,000 institutional profiles. Most of the journal and proceeding publications from Scopus and IEEE show a lack of academia view or fundamental discussion on corrosion in electronic packaging. However, corrosion stories and discussions on the subject matter have been widely reported in the oil and gas industry. Engineers from the electronic industry published their works in IEEE but less in Scopus or
journal publications. The knowledge on corrosion is important to be disseminated, so that people from industries can refer to and apply it in their daily routines works.

In the electronic era, electronic packaging is the backbone of the hardware. The functionality and the structural integrity of the hardware is very much depending on the electronic packaging. Electronic packaging serves multifunction, power management, reliability, miniaturization, and thermal management. The reliability of the electronic packaging is varying by the mechanical factor, thermal aspect, and environmental and service conditions. A huge amount of research and development has been carried out either by both industrial people and academia. Either doing applied research or fundamental research on corrosion in electronic packaging. The objectives of this review paper are to highlight a case study on reliability issues in electronic packaging, which is corrosion in wire bonding, corrosion in leadframe and corrosion in solder. Figure 1 shows the side-view schematic of integrated circuit packaging and Figure 2 shows an integrated circuit of multi-component attached to the printed circuit board. The schematics of electronic packaging show that mostly metallic materials are involved in the electronic package. Other materials to construct the electronic package such as polymer materials for epoxy mold compound, Si for Si wafers, polymer and metallic materials for printed circuit boards, and the circuit is made from copper, interconnection from metallic materials.

Figure 1. Schematic side-view of integrated circuit packaging: (a) face up and (b) face down.

Figure 2. Various components attached to the printed circuit board.
Corrosion in electronic packaging involves metallic materials. The scope of this review involves corrosion occurrence on the metallic materials of the electronic packaging. Corrosion occurrence will lead to functionality failure. The failure of the semiconductor packaging will lead to the failure of the device. Since modern electronic devices, have application in automotive and transportation, thus this will lead to catastrophic failure in human beings. For application, household applications, the severity of failure is less as compared to automotive and transportation applications. In terms of structural integrity to protect the electronic functionality, the IC and metallic structure such as wire bonding, leadframe, and interconnect are neatly encapsulated by an epoxy mold compound. Assuming that the EMC is capable of fully giving protection to the internal structure then the reaction of metallic materials with the environment to produce corrosion activity will be eliminated. However, seldomly reported cases related to corrosion occurrence of the metallic structure in the electronic packaging from the perspective of the manufacturer and consumer. Thus, this topic becomes concern and point of interest for manufacturers or industrial point of view. The aim of this work to investigate and analyze activities on corrosion of electronic packaging through a scholarly demographic approach from academic and industry perspectives. Based on our 20 years of experience in collaborative works between academia and the semiconductor packaging industry, we realize that different research cultures and outputs become big challenges. However, this culture provides a good opportunity effectively solved the problem i.e., in this case, the corrosion in electronic packaging by having a clear overview of the demographic and direction of interest.

2. Methodology

This review used IEEE Xplore and Scopus search engines to extract publications from the year of 2010 until 2020. The first criterion to include in the search is the keyword. Three type keyword combination consisted of (“corrosion” and “wire bonding”), (“corrosion” and “leadframe”) and (“corrosion” and “solder”) as shown in Figure 3. The corrosion keyword was chosen because the main interest is to review on corrosion in the electronic packaging industry. The second keyword to be combined with “corrosion” are wire bonding, leadframe, and solder. The reason for these keywords’ selection is related to the corrosion occurs in the metallic part mainly for the electronic packaging. The collected published works are limited to journals and conferences only. The documentation such as the chapter in books, magazines, and standards were excluded in the selected published work. The screening abstract was checked thoroughly to ensure the publications are related to the keywords. The article in journals and conferences in both search engines were downloaded in full papers. We went through all the publications and analyze them according to subject matter corrosion in electronic packaging, affiliation, and acknowledgment. Next, the publications were analyzed by dividing them into three categories according to the demographic of works carried out such as (“collaborative work”, “industry” and “academia”). The publications numbers were sorted according to the search keywords (“corrosion” and “wire bonding”), (“corrosion” and “leadframe”) and (“corrosion” and “solder”) and categories (“collaborative work”, “industry” and “academia”) together with publication year and publication type. A research institute or agency is categorized as an industry affiliation. The category of collaborative work between industry and academia was emphasis more in the analysis and discussion. From this finding, we further analyzed corrosion in electronic packaging were gain interested parties from the industry over the past 10 years.
3. Result and Discussion

This review separates the publication type into conference and journal. This is due to the hypothesis that conference publications are more contributed by industry while journal publications are dominated by academia. Publications from industry are more on the practical work or issues in daily routine work while publications from academia are more on the fundamental aspect, theoretical and academic points of interest. The findings show that conference publication is significantly contributed by industry while the major player in journal publications is academia. Research activities carried out at university are more to lab scale while research activities by industrial are on the actual sample. Collaboration work publication is considered by having affiliation from both academia and industry. It shows the joint publication contributed scholarly from both parties. However, if the paper written up by academia and the industrial partner was acknowledged in the acknowledgment section, the paper will not be considered in this hypothesis as collaboration work because the work by the academia is sponsored by the industry. The limitation of this review analysis is the affiliation address.

3.1. IEEE Search Engine

Figure 4 shows the publication number from IEEE Xplore from 2010 until 2020. Based on the keyword (“corrosion” and “wire bonding”), 168 publications consisting of 7 journals and 161 conference papers have been published. For keywords (“corrosion” and “leadframe”) consist of 5 publications of 1 journal and 4 conference papers and the keyword (“corrosion” and “solder”) is 145 publications consisting of 12 journals and 133 conference papers. It is found that the publications from keyword (“corrosion” and “wire bonding”) are higher than another keyword. Figure 5 shows the trend of publications for all type keywords and year. Among the three keywords selected, (“corrosion” and “wire bonding”) and (“corrosion” and “solder”) shows every year published conference papers. The highest number publication for (“corrosion” and “wire bonding”) keyword are conference paper...
in 2010 and 2016. For ("corrosion" and “leadframe”) keyword, journal publication is only one in 2010 while for conference paper published with same quantity in 2012, 2016, 2018 and 2020. The highest number of publications ("corrosion" and “solder”) keyword in the conference paper category are in 2015 and 2016 with 16 papers.

Figure 4. Number of publications for conference and journal from 2010 to 2020 in IEEE Xplore.

Figure 5. Total publications for conference and journal from 2010 to 2020 in IEEE Xplore.

It is observed that more publications are in the conference as compared to the journal. This is due to publishing at conference being easier which take a shorter time in terms of the submission process whereby fast feedback approximately 1–2 months depending on the type of conference. People are more preferring to present their works at the conference because the conference is more interactive with an international audience with similar backgrounds or fields of expertise. The advantages of presenting at the conference are easy negotiation and feedback. This is different from the journal publication whereby the paper consists of some fundamentals and theories. The journal paper undergoes frequently peer-reviewed. The papers will carefully be evaluated for errors and possibility rewritten a couple of times and sometimes take longer time approximately more than 2 months and nearly one year to be published. The challenge to publish in high-impact journal compared to a conference paper is due to high-quality paper with deep analysis.
3.1.1. Publication Based on Keywords “Corrosion” and “Wire Bonding”

Figure 6 shows the number of publications for the keywords “corrosion” and “wire bonding” in conferences and journals from 2010 to 2020 from IEEE Xplore. It has been discovered that the number of publications contributed by industry (104 papers) is greater than that of academia (19 papers) and collaborative work (46 papers). As shown in Figure 7, the number of conference papers published by industry is 104, followed by collaborative work with 42 papers and academia with 16 papers. It is also observed that the number of conference publications is higher than the number of journal publications for all categories, with four journals from collaborative work and three from academia. There is no journal publication from the industry from 2010 until 2020.

![Figure 6](image_url)

**Figure 6.** Publication number of keywords “corrosion” and “wire bonding” in conference and journal 2010 to 2020 from IEEE Xplore after the source of affiliation analysis.

![Figure 7](image_url)

**Figure 7.** Total publication of keywords “corrosion” and “wire bonding” in conferences and journal from 2010 to 2020 from IEEE Xplore.
3.1.2. Publication Based on Keywords “Corrosion” and “Leadframe”

Figure 8 shows the number of publications for the keywords “corrosion” and “leadframe” in conferences and journals from 2010 to 2020 from IEEE Xplore. It is observed that only from the category academia published their works in journals and conference as presented in Figure 9. There are five publications whereby journal publication only one in 2010 and the other four publications were conference papers published in 2012, 2016, 2018 and 2020.

![Figure 8](image8.png)

**Figure 8.** Publication number of keywords “corrosion” and “leadframe” in conference and journal 2010 to 2020 from IEEE Xplore.

3.1.3. Publication Based on Keywords “Corrosion” and “Solder”

Figure 10 shows the publication number of the keyword “corrosion” and “solder” in conferences and journals from 2010 to 2020 from IEEE Xplore. It has been revealed that the number of publications contributed by academia (76 papers) is greater than that of industry (55 papers) and collaborative work (14 papers). As shown in Figure 11, the number of conference papers published by academia is 67 papers, followed by industry with 53 papers and collaborative work with 13 papers. It is also observed that the number of conference publications is higher than the number of journal publications for all categories, with 10 journals from academia and two journals from the industry. Data shows that only conference papers were published by collaborative work from 2010 until 2019.

![Figure 9](image9.png)

**Figure 9.** Total publication of keywords “corrosion” and “leadframe” in conferences and journal from 2010 to 2020 from IEEE Xplore.
Figure 10. Publication number of keywords “corrosion” and “solder” in conference and journal 2010 to 2020 from IEEE Xplore.

Figure 11. Total publication of keywords “corrosion” and “solder” in conferences and journals from 2010 to 2020 from IEEE Xplore after the source of affiliation analysis.

3.1.4. Publication Based on Collaborative Works

Figure 12 shows the total number of publications for three types of keywords used. It is found that 13 and 44 publications from collaboration works for keywords (“corrosion” and “wire bonding”) and (“corrosion” and “solder”), respectively. While there is no collaborative work on (the “corrosion” and “leadframe”) keywords as in Figure 13.

Figure 12. Collaborative work in conference and journal for 2010 to 2020 from IEEE Xplore.
Figure 13. Total number of collaborative work in conferences and journals for 2010 to 2020 from IEEE Xplore.

Table 1 shows the collaboration works under “corrosion” and “wire bonding” and “corrosion” and “solder” from the IEEE search engine. It is shown that there are 44 collaboration publications under “corrosion” and “wire bonding” consisting of 40 conferences and 4 journals. All the journals were published in IEEE Transactions on Components, Packaging, and Manufacturing Technology journal. Out of 44 documents for collaborative work under “corrosion” and “wire bonding” keywords, it is found that only 26 collaborative works are between different academia and industries. Based on demographic, it is discovered that Asia countries dominated the collaboration works under the “corrosion” and “wire bonding” keywords. The Asia countries participating in the collaboration such as Malaysia, Singapore, Thailand, China, Korea, and Japan. The other participating countries are the United States from North America and Europe countries by German and Netherlands. It is observed that Asia countries collaborate with Asia, North America, and Europe countries. Only Netherlands collaboration work [1] does not collaborate with outside countries. From Table 1, it is noticed that the collaboration between Wire Technology Company, Ltd. and National Taiwan University only published two journals whereby other collaborations typically published conference papers [2,3]. This collaboration is located in Taiwan, China, and the collaboration work was supported by the Industrial and Academic Cooperation Program and a research grant from the Ministry of Science and Technology Taiwan. Another successful collaboration work is by Pradeep Lall from Auburn University, United States collaborating with Texas Instruments, United States. His works have published in eight conference papers and two journals. The collaboration work was supported by a research grant from the Semiconductor Research Corporation (SRC) and Members of the NSF-CAVE3 Research Center at Auburn University.

Table 1. Collaboration works under the keywords “corrosion” and “wire bonding” in conferences and journals from the IEEE search engine.

| Title of Paper | Refs | Remarks |
|----------------|------|---------|
| Methodology to determine high precision variation in the electrical resistance of copper wires due to corrosion | [4] | Collaboration work involved two branches of Infineon Technologies in Singapore and Germany with Nanyang Technological University, Singapore. This work was funded by Singapore Economic Development Board and Infineon Technologies Asia Pacific Pte Ltd. |
| Corrosion of Copper Wire bonded Packages by Chlorine Containing Foreign Particles | [5] | Collaboration work in United States between NXP Semiconductors as an industry partner and The University of Texas at Austin as an academia partner. This work got technical support from the management. |
Table 1. Cont.

| Title of Paper                                                                 | Refs | Remarks                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|-------------------------------------------------------------------------------|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Investigation of mechanism of corrosion resistance of Pd coated Cu wire joint by pseudo process | [6]  | Collaboration work in Japan between Renesas Electronics Corporation and National Institute of Advanced Industrial Science and Technology (AIST). Part of this work was conducted at the AIST Nano-Processing Facility and supported by the “Nanotechnology Platform Program” of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.                                                                                                     |
| Reduction of Ag Corrosion Rate During Decapsulation of Ag Wire Bond Packages | [7]  | Collaboration work between two countries, Samsung Electronics in Korea and Georgia Institute of Technology, Atlanta, United States.                                                                                                                                                                                                                                                                                                                                                     |
| Influence of Copper Wire Material Additive Elements to the Reliability of Wire Bonded Contacts | [8]  | Collaboration work between two countries, a well-known institute Fraunhofer Institute, IWM in Germany with Nippon Micrometal Corporation in Japan.                                                                                                                                                                                                                                                                                                                                                                                      |
| How Copper Wire Material Additive Elements Effect the Reliability of Wire Bonded Contacts in HAST testing | [9]  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| Investigation of mechanical and microstructural properties of a new, corrosion resistant gold-palladium coated copper bond wire | [10] |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| A New Reliable, Corrosion Resistant Gold-Palladium Coated Copper Wire Material | [11] |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| Influence of copper wire material to corrosion resistant packages and systems for high temperature applications | [12] |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| Novel Corrosion Prevention Treatments for Cu Wire Bonded Device to Improve Bonding Reliability | [13] | Collaborative work between one academia, University of North Texas with two branches of Texas Instruments Inc. located in Dallas and Santa Clara. The authors acknowledge supports from Semiconductor Research Corporation (SRC) and technical assistance from UNT Materials Research Facility.                                                                                                                         |
| An Evaluation of Effects of Molding Compound Properties on the Reliability of Ag Wire Bonded Components | [14] | Collaborative work between seven authors from Purdue University and Juniper Networks. The work was done in United States.                                                                                                                                                                                                                                                                                                                                                                                |
| Effects of Pd distribution at free air ball in Pd coated Cu wire               | [15] | One of the authors of this paper having two affiliations of MK Electron Co., Ltd. and Myongji University. We believe that he had engage in his postgraduate study at Myongji University. This work was done in Korea.                                                                                                                                                                                                                                                                                               |
| Corrosion Behavior of Cu-Al Intermetallic Compounds in Copper Wire Bonding in Chloride-Containing Accelerated Humidity Testing | [16] | Collaborative work between two authors from NXP Semiconductors Guangdong Ltd. and two authors from Hong Kong University of Science & Technology. The authors also have acknowledged contribution from other branches of NXP Semiconductors located in Hong Kong for research materials and technical support.                                                                                           |
| Investigation of Cu wire neck crack under thermal cycling test               | [17] | Collaborative work in Hong Kong, China between NXP Semiconductors HK as industry partner and Hong Kong University of Science and Technology as academia partner.                                                                                                                                                                                                                                                                                                                                         |
| Influence of the zinc-oxide/salt content in the aluminum soldering flux on interfacial microstructure and mechanical property of Sn-0.7Cu/Al joints in assembling LED lighting components | [18] | Collaborative work between South China University of Technology and Guangdong Welding Institute. Both industry and academia are in Guangzhou, China. The collaboration work was supported by three research grants i.e., National Natural Science Foundation of China, Science and Technology Planning Project of Guangdong Province and Guangdong Provincial Key Laboratory of Advanced Welding Technology.                                                                                                                                 |
| Evaluation of the corrosion performance of Cu-Al intermetallic compounds and the effect of Pd addition | [19] | Collaborative work between two branches of Kulicke & Soffa Pte. Ltd. located at Singapore and United States with Nanyang Technological University, Singapore. One of the authors having both industry and academia affiliation. We believe that the author pursuing his postgraduate study as the work was financially supported by Economic Development Board (EDB) under Industrial Postgraduate Programme (IPP). The authors also acknowledge technical and expertise from Prof Daniel Mandler from The Hebrew University of Jerusalem, Dr Zviad Tsakadze from NTU FACTS, Vinod Kumar from NTU, Dr Sudesh L. Wijesinghe and Tan Yong Teck from SIMTech. |
| Evaluation of Corrosion Resistance of Ag-Alloy Bonding Wires for Electronic Packaging (journal) | [3]  | This collaborative paper published in journal. The work is in Taiwan, China by five authors from industry, Wire Technology Company, Ltd. and two authors are from National Taiwan University. The work was partly supported by Industrial and Academic Cooperation Program through Wire Technology Company, Ltd., and Ministry of Science and Technology, Taiwan, under a research grant.                                                                                                                                                                                                 |
| Materials Characteristics of Ag-Alloy Wires and Their Applications in Advanced Packages (journal) | [2]  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| Title of Paper                                                                 | Refs | Remarks                                                                                                                                 |
|------------------------------------------------------------------------------|------|-----------------------------------------------------------------------------------------------------------------------------------------|
| Influence of Au film thickness on surface morphology and properties of substrate with Ni/Au microcones | [20] | Collaborative work in Shanghai, China. Two authors are from Shanghai Jiao Tong University collaborate with two authors from SanDisk Semiconductor Co., Ltd. The research was funded by National Basic Research Program of China and National Nature Science Foundation of China. |
| The corrosion behavior of Ag alloy wire bond on Al pad in molding compounds of various chlorine contents under biased-HAST | [21] | Collaborative work in between ASE Global in Taiwan and Japan as industry partner and National Cheng Kung University, Taiwan as academia partner. |
| The corrosion performance of Cu alloy wire bond on Al pad in molding compounds of various chlorine contents under biased-HAST | [22] |                                                                                                                                 |
| 3-D Numerical Multiphysics Model for Cu-Al Wire Bond Corrosion                | [23] |                                                                                                                                 |
| A Novel Numerical Multiphysics Framework for the Modeling of Cu-Al Wire Bond Corrosion under HAST Conditions | [24] |                                                                                                                                 |
| Numerical Multiphysics Model for Cu-Al Wire Bond Corrosion Subjected to Highly-Accelerated Stress Test | [25] |                                                                                                                                 |
| Package-level multiphysics simulation of Cu-Al WB corrosion under high temperature/humidity environmental conditions | [26] | The main author of this paper is from academia, Auburn University. They collaborate with industry, Texas Instruments. All the work were done in United States and supported by a research grant from the Semiconductor Research Corporation (SRC) and Members of NSF-CAVE3 Research Center at Auburn University. |
| Development of Model for Identification of Process Parameters for Wet Decapsulation of Copper–Aluminum Wirebond in PEMs (journal) | [26] |                                                                                                                                 |
| Model for Interaction of EMC Formulation with Operating Current and Reliability of Cu-Al Wirebonds Operating in Harsh Environments | [27] |                                                                                                                                 |
| Microstructural Indicators for Prognostication of Copper-Aluminum Wire Bond Reliability Under High-Temperature Storage and Temperature Humidity (journal) | [28] |                                                                                                                                 |
| Multiphysics Life-Prediction Model Based on Measurements of Polarization Curves for Copper-Aluminum Intermetallics | [29] |                                                                                                                                 |
| Prognostic indicators for Cu-Al wirebond degradation under operation at elevated temperature and combined temperature humidity | [30] |                                                                                                                                 |
| Prognostication of copper-aluminum wirebond reliability under high temperature storage and temperature-humidity | [31] |                                                                                                                                 |
| Low-cost silver alloy wire bonding with excellent reliability performance      | [32] | Collaborative work in Taiwan involved between Elite Semiconductor Memory Technology Inc. as industry partner and Department of Physics, Tunghai University as academia partner. This work acknowledges few names including the Vice President of Elite Semiconductor Memory Technology Inc., United States. The authors also acknowledge Siliconware Precision Industries Co., Ltd. for the support in the packaging processes. |
| Microwave Induced Plasma decapsulation of thermally stressed multi-tier copper wire bonded IC packages | [1]  | This paper involved three department from Delft University of Technology, Netherlands collaborates with industry namely MASER Engineering also located in Netherlands. MASER is a company that provide Reliability Test and Failure Analysis Services to the semiconductor and electronic systems industry since 1993. This paper acknowledges Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR); iNEMI’s Copper Wire Bonding Reliability Consortium for providing the samples and some colleagues for experiments support. |
| Investigation of fluorine induced probe marker discoloration                     | [33] | Collaborative works from industry and academia in Taiwan. 6 authors are from Elite Semiconductor Memory Technology Inc collaborate with one author from Tunghai University. The paper also acknowledges technical support from the manager and vice president of Elite Semiconductor Memory Technology Inc. |
Table 1. Cont.

| Title of Paper                                                                 | Refs | Remarks                                                                                                                                 |
|--------------------------------------------------------------------------------|------|-----------------------------------------------------------------------------------------------------------------------------------------|
| Wearout reliability study of Cu and Au wires used in flash memory fine line BGA package | [34] | This paper is authored by CL Gan which having affiliation from industry (Spansion Penang Malaysia) and academia (UniMAP, Malaysia). It also authored by two researchers from other branches of Spansion in Thailand. The paper acknowledges an appreciation to Gene Daszko and Tony Reyes from Spansion which located at Sunnyvale, California, United States, Francis Classe from Cypress Semiconductor Corporation) and HL Chong from Spansion Penang Malaysia). |
| Investigation of palladium coverage on free air balls of palladium-coated copper wires | [35] | Collaborative works from ASE Assembly & Test (Shanghai) Limited, China and Fudan University of China. The industry partner offers packaging and testing services for semiconductors such as integrated circuit (IC) design, assembly & test, wafer probing, and final test services. |
| Investigation of palladium coverage on bonded balls of palladium-coated copper wires | [36] | Collaborative works involved semiconductor assembly company, Powertech Technology Inc. located in China with a manufacture of non-conventional bonding wires (such as copper, palladium coated copper and silver alloy fine wires) Semicon Fine Wire Pte Ltd. located in Singapore. These two industries collaborated with 1TE College Central, Singapore. |
| Pd effects on the reliability in the low cost Ag bonding wire                   | [37] | Mr Jong-Soo Chu is having two affiliation which is MK Electron and Seoul National University, probably he further his study in 2010. The rest authors are from MK Electron collaborate with Samsung Electronics. All affiliations are located at Korea. |
| On the intermetallic corrosion of Cu-Al wire bonds                               | [38] | Collaboration work from well-known Institute Fraunhofer Institute, IWM, Germany with NXP Semiconductors. We believe that this work involved many branches of NXP Semiconductors involving 15 researchers. This work supported by academia, Prof. Jingshen Wu from The Hong Kong University of Science and Technology (HKUST). |
| A study on fine pitch Au and Cu WB integrity vs. Ni thickness of Ni/Pd/Au bond pad on C90 low k wafer technology | [39] | Four researchers from Freescale Semiconductor Malaysia collaborate with four researchers from Freescale Semiconductor Texas, United States and one researcher from MMU Malaysia. This work got full support from MMU management. |
| High temperature automotive application: A study on fine pitch Au and Cu WB integrity vs. Ni thickness of Ni/Pd/Au bond pad on C90 low k wafer technology | [40] | Collaboration work between industry (ProMat Consultants in Singapore) and academia (ITE College Central). The project was funded by the World Gold Council. |
| Comparsion of Au/Al and Cu/Al in wirebonding assembly and reliability           | [41] |                                                                                                                                 |
| Comparsion of Au/Al and Cu/Al in wirebonding assembly and reliability           | [41] |                                                                                                                                 |
| Effects of moisture on reliability of gold and copper ball bonds                 | [42] |                                                                                                                                 |

Table 2 shows the collaboration publications under “corrosion” and “solder”. It is found that only 13 conference papers were published. Out of 13 documents for collaborative work under “corrosion” and “solder” keywords, it is found that only 12 collaborative works between different academia and industries. Based on demographic, it is discovered that Europe countries consists of United Kingdom, Germany, and Hungary have dominated the collaboration works under “corrosion” and “solder” keywords. The other participating countries are China and Korea from Asia and United States and Canada from North America countries. Collaboration work by done by Y. Cheng et al. [43] have published conference papers whereby the academia, Guilin University of Electronic Technology, China has collaborated with Hengchang Electronic Technology Lit. Co. Their works have been supported by Guilin Bureau of Science and Technology and Guangxi Bureau of Science and Technology and Guangxi key lab.
| Title of Paper                                                | Refs | Remarks                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|---------------------------------------------------------------|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Electrochemical corrosion in electric energy meters           | [44] | Collaboration work in China between the industry, Southern Power Grid Science Research Institute Co., Ltd., Guangzhou with three authors and the academia, Huazhong University of Science and Technology Wuhan with three authors.                                                                                                                                                                                                                                                                                  |
| Innovative Socketable and Surface-Mountable BGA Interconnections | [45] | Collaboration work in United States between Georgia Institute of Technology, Atlanta and Intel Corporation. This work was sponsored by the Semiconductor Research Corporation (SRC). The authors also acknowledge another industry, Atotech GmbH for providing the research material, facilities, and technical support.                                                                                                                                                                                                                           |
| Flexible connection for reflow free super fine pitch QFP SMT components | [43] | Collaboration work in China involving Guilin University of Electronic Technology consist of seven authors and Hengchang Electronic Technology Lit. Co consists of three authors. The authors acknowledge the Guilin Bureau of Science and Technology and Guangxi Bureau of Science and Technology and Guangxi key lab for facilities support of this work.                                                                                                                                            |
| An investigation into the effect of dry bake on the solderability degradation of electrodeposited tin finishes | [46] | Collaboration work between two countries, United Kingdom and China. The academia partner is Loughborough University with five authors and industry partner is Huawei Technologies Co. Ltd. with two authors.                                                                                                                                                                                                                                  |
| Eternal Packages: Liquid Metal Flip Chip Devices               | [47] | Collaboration work in Canada involving three authors from Universite de Sherbrooke, Sherbrooke and two authors from IBM Canada Limited, Bromont. This work was supported in part by the NSERC/IBM Canada Industrial Research Chair in Smarter Microelectronic Packaging for Performance Scaling, with financial contributions from the IBM Corporation, the Natural Sciences and Engineering Research Council of Canada, PROMPT, and the Universite de Sherbrooke.                                                                 |
| Removed organic solderability preservative (OSP) by Ar/O\textsubscript{2} microwave plasma to improve solder joint in thermal compression flip chip bonding | [48] | This paper is authored by three authors from ASE Group, China and three authors from National Cheng Kung University, China. This collaboration work involved two department of the academia partner, i.e., Department of Materials Science and Engineering and Department of Chemical Engineering. For this collaboration, the industrial partner has provided financial support.                                                                                                                                 |
| Reliability study on chip capacitor solder joints under thermo-mechanical and vibration loading | [49] | Collaboration work in Germany between Fraunhofer IKTS-MD, Dresden and Continental Automotive GmbH, Regensburg.                                                                                                                                                                                                                                                                                                                                                                             |
| Failure analysis and case study of plastic encapsulated microelectronics | [50] | Collaboration between China Electronics Product Reliability and Environmental Testing Institute as industry partner with Peking University, China as academia partner. Both parties have contributed in terms of providing failure samples for analysis, and failure analysis team and research facilities.                                                                                                                                                                                                                   |
| Solder joint properties of Sn-Ag-Cu solders on environmental-friendly plasma surface finish | [51] | Collaboration between two industries partner, Advanced Welding and Joining Technology Center, KITECH and JESAGI HANKOOK Ltd. with Andong National University. The authors acknowledge the financial support from Ministry of Knowledge Economy. The location of this work is in Korea.                                                                                                                                                                                                                 |
| Investigation of the oxidation process at the copper-solder interface with atomic force microscopy | [52] | Collaboration work in Hungary between Budapest University of Technology and Economics and Preclinical Imaging and Biomarker Centre. The academia got financial support for this work.                                                                                                                                                                                                                                                                                                                                                             |
| Study on wettability and corrosivity of a new no-clean flux for lead-free solder paste in electronic packaging technology | [53] | Collaboration work between one author from Advanced Technology & Materials Co., and three authors from Henan Polytechnic University. This work was done in China.                                                                                                                                                                                                                                                                                                                                                   |
| Packaging of high-power semiconductor laser arrays using a novel macro-channel cooler | [54] | Collaboration work in China between Xi’an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences and Xi’an Focussight Technologies Co. This work was supported by the project of the “Hundred Talents Research Fund of Chinese Academy of Sciences”, the Instrument Developing Project of the Chinese Academy of Sciences, and the National High Technology Research and Development Program of China.                                                                                                               |
3.2. Scopus Search Engine

Figure 14 shows the three keywords selected ("corrosion" and "wire bonding"), the ("corrosion" and "leadframe") and ("corrosion" and "solder") from 2010 until 2020. It is observed that journal publications from combination keywords of corrosion and solder show consistency highest number among others. In Figure 14, the keywords ("corrosion" and "solder") show the highest number of journal publications at the amount of 548 consisting of 338 journal and 210 conference papers followed by the ("corrosion" and "wire bonding") keywords with the total amount of 141 publications consisted of 40 journals and 101 conference papers. The least amount of publication for ("corrosion" and "leadframe") keywords with total publications of 5 consisted of 1 journal and 4 conference papers from 2010 and 2020. For all types of keywords and years, the trend in publications is shown in Figure 15. In the search results for the three keywords chosen, ("corrosion" and "wire bonding") and ("corrosion" and "solder"), every year published conference papers are shown since 2010 until 2020. For the keywords ("corrosion" and "solder"), the highest number of journal papers published is 42 in 2015 while conference papers in 2013 with a total of 16 articles. For the keywords ("corrosion" and "leadframe"), only 1 journal publication was published in 2013, whereas the same number of conference papers were published in 2012, 2017, 2018, and 2020.

![Figure 14. Publication number of conference and journal 2010 to 2020 from Scopus.](image)

![Figure 15. Number of publications for conference and journal 2010 to 2020 from Scopus.](image)

3.2.1. Publication Based on Keywords “Corrosion” and “Wire Bonding”

Based on Scopus data, Figure 16 shows the number of articles containing the keywords “corrosion” and “wire bonding” in conferences and journals from 2010 to 2020. It has been
found that the number of publications provided by industry (77 papers) is higher than the number of publications contributed by collaborative work (33 papers) and academia (31 papers) as shown in Figure 17. Contribution from conference publication categories has shown that the industry has published total 66, followed by collaborative work with a total of 20 and academia is 15. Also noted is that the number of conference publications exceeds the number of journal publications from industry and collaborative works affiliations.

Figure 16. Publication number of keyword “corrosion” and “wire bonding” in conference and journal 2010 to 2020 from Scopus after source of affiliation analysis.

Figure 17. Total publication of keyword “corrosion” and “wire bonding” in conference and journal 2010 to 2020 from Scopus after source of affiliation analysis.

3.2.2. Publication Based on Keywords “Corrosion” and “Leadframe”

Figure 18 shows the number of publications for the keyword’s “corrosion” and “lead-frame” in conferences and journals from 2010 to 2020 from Scopus. It has been discovered that the number of publications contributed by industry (5 papers) while for academia and collaborative works no publication with keywords “corrosion” and “leadframe”. The number of conference papers published by industry as shown in Figure 19 is 4 and only 1 in journal publications since 2010 until 2020.
3.2.3. Publication Based on Keywords “Corrosion” and “Solder”

Figure 20 shows the number of publications for the keywords (“corrosion” and “solder”) in conferences and journals from 2010 to 2020 from Scopus. It is clearly observed that the publication from academia has been dominant as compared to industry. In Figure 20, it has been discovered that the highest number of publications contributed by academia with total publications 248 articles (237 journal and 111 conference papers) while for and collaborative works is 75 articles (49 journals and 26 conference papers) with keywords “corrosion” and “solder” since 2010 until 2020. From the Figure 21, it is shown that the academia is more preferable to publish their works in journals articles rather that conference papers. The industry showed less interest to published in journal rather than conference. The total number of collaboratives works between academia and industry showed competitive numbers with industry.
3.2.4. Publication Based on Collaborative Works

Figure 22 shows the number of publications based on collaborative works in conferences and journals from 2010 to 2020 from Scopus. There is no collaborative works found for keywords (“corrosion” and “leadframe”). It has been discovered that the highest number of publications contributed by collaborative works for keywords (“corrosion” and “solder”) for journal followed by conference with the total number of 49 and 26 articles in Figure 23. The second highest collaborative works showed that keywords of (“corrosion and wire bonding”) with the total number of articles is 13 for journal and conference is 20 articles. When we analysis of collaborative works from Scopus publication, it is shown that less or no attempt were existed since 2010 until 2020 for keywords (“corrosion” and
“leadframe”). From this finding, there is an opportunity to initiate the collaborative works emphasized on corrosion and leadframe in electronic packaging (Tables 3 and 4).

Figure 22. Collaborative work in conference and journal for 2010 to 2020 from Scopus after source of affiliation analysis.

Figure 23. Total number collaborative work in conference and journal for 2010 to 2020 from Scopus after source of affiliation analysis.

Table 3. Collaboration works under keywords “corrosion” and “wire bonding” in conference and journal from Scopus search engine.

| Title                                                                 | Refs | Remarks                                                                                                                                   |
|----------------------------------------------------------------------|------|------------------------------------------------------------------------------------------------------------------------------------------|
| Corrosive degradation evaluation of semi-parallel wire cables        | [55] | Collaboration works in China between Central South University and Engineering Technology Research Center for Prefabricated Construction Industrialization of Hunan Province. |
| Corrosion-induced degradation and its mechanism study of Cu–Al interface for Cu-wire bonding under HAST conditions | [56] | Collaboration works in 2 countries China and United States, whereby National Cheng Kung University, Tainan, Texas Instruments Taiwan Limited Inc. and Panasonic Energy of North America. |
| Corrosion of Gold by a Nanoscale Gold and Copper Beltlike Structure  | [57] | Collaboration works in 2 countries United Kingdom and Japan, whereby University of Oxford, Diamond Light Source Ltd., and JEOL Ltd.                |
| The bondability and reliability of a ternary Ag alloy wire on an Al bonding pad under N2-free conditions | [58] | Collaboration works in South Korea between Samsung Electronics Co., Ltd. and Sungkyunkwan University.                                      |
| Title                                                                 | Refs        | Remarks                                                                 |
|----------------------------------------------------------------------|-------------|-------------------------------------------------------------------------|
| BGA substrate outgassing negative impact study on Cu wire bonding     | [59]        | Collaboration works in China between Tianjin University and NXP Semiconductor (China) Ltd. |
| Microstructural Indicators for Prognostication of Copper-Aluminum Wire Bond Reliability Under High-Temperature Storage and Temperature Humidity | [19]        | Collaboration works in United States between Auburn University and Texas Instruments. |
| Materials Characteristics of Ag-Alloy Wires and Their Applications in Advanced Packages | [19]        | Collaboration works in China between Wire Technology Company, Ltd., and National Taiwan University. |
| Effect of palladium on the mechanical properties of Cu and Cu-Al intermetallic compounds | [60]        | Collaboration works in Singapore between Nanyang Technological University, Kulicke and Soffa Pte. Ltd., 6 and A STAR (Agency for Science Technology and Research). |
| Evaluation of the corrosion performance of Cu-Al intermetallic compounds and the effect of Pd addition | [19]        | Collaboration works in 2 countries Singapore and United States whereby Kulicke and Soffa Pte. Ltd., Nanyang Technological University and Kulicke and Soffa Industries Inc. |
| Effect of palladium on the mechanical properties of Cu-Al intermetallic compounds | [60]        |                                                                           |
| Ultra-fine pitch palladium-coated copper wire bonding: Effect of bonding parameters | [61]        |                                                                           |
| Effect of thickness and phosphorus content on Au/Pd/Ni(P) metal finish of printed circuit board | [62]        | Collaboration works in 2 countries China and Philippines, whereby Chung Yuan Christian University, OMG (Asia) Electronics Company Limited and Mapua Institute of Technology Intramuros. |
| Copper wire bonding concerns and best practices                        | [63]        | Collaboration works in 2 countries United States and Singapore, whereby CALCE Electronic Products and Systems Center, University of Maryland and Nanyang Technological University. |
| Corrosion study and intermetallics formation in gold and copper wire bonding in microelectronics packaging | [64]        | Collaboration works in Singapore between Institute of Technical Education, and Promat Consultants. |
| Methodology to determine high precision variation in the electrical resistance of copper wires due to corrosion | [4]         | Collaboration works in 2 countries Singapore and Germany whereby Nanyang Technological University, Infineon Technologies Ag and Infineon Technologies Asia Pacific. |
| 3-D numerical multiphysics model for Cu-Al wire bond corrosion          | [23]        | Collaboration works in United States between Auburn University and Texas Instruments. |
| Multiphysics Life-Prediction Model Based on Measurements of Polarization Curves for Copper-Aluminum Intermetallics | [29]        |                                                                           |
| An Evaluation of Effects of Molding Compound Properties on the Reliability of Ag Wire Bonded Components | [14]        | Collaboration works in United States between Purdue University and Juniper Networks. |
| Mechanistic Investigation and Prevention of Al Bond Pad Corrosion in Cu Wire-Bonded Device Assembly | [65]        | Collaboration works in United States between University of North Texas, Texas Instruments Inc., and Texas Instruments Inc. |
| Corrosion Behavior of Cu-Al Intermetallic Compounds in Copper Wire Bonding in Chloride-Containing Accelerated Humidity Testing | [16]        | Collaboration works in China between NXP Semiconductors Guangdong Ltd., Hong Kong University of Science and Technology and Clear Water Bay. |
| Evaluation of the corrosion performance of Cu-Al intermetallic compounds and the effect of Pd addition | [19]        |                                                                           |
| Influence of Au film thickness on surface morphology and properties of substrate with Ni/Au microcones | [20]        | Collaboration works in China between Shanghai Jiao Tong University and Semiconductor Co., Ltd. |
| Prognostic indicators for Cu-Al wirebond degradation under operation at elevated temperature and combined temperature humidity | [30]        |                                                                           |
| High temperature storage and hast reliability of Copper-Aluminum wirebend interconnects | [66]        | Collaboration works in United States between Auburn University and Texas Instruments. |
| Prognostication of copper-aluminum wirebend reliability under high temperature storage and temperature-humidity | [31]        |                                                                           |
| Investigation of fluorine induced probe marker discoloration             | [33]        | Collaboration works in China between Elite Semiconductor Memory Technology Inc., and Tunghai University. |
| Low cost silver alloy wire bonding with excellent reliability performance | [32]        | Collaboration works in China between Elite Semiconductor Memory Technology Inc., and Tunghai University. |
| Palladium-coated and bare copper wire study for ultra-fine pitch wire bonding | [67]        | Collaboration works in 2 countries Singapore and United States whereby between Kulicke and Soffa Pte. Ltd., and Nanyang Technological University. |
| Pd-coated Cu wire bonding reliability requirement for device design, process optimization and testing | [68]        | Collaboration works in 2 countries China and United States Xilinx Inc., Siliconware Precision Industries Co., Ltd., Kulicke and Soffa Industries, Inc., and University of Alabama. |
Table 3. Cont.

| Title                                                                 | Refs | Remarks                                                                 |
|----------------------------------------------------------------------|------|-------------------------------------------------------------------------|
| Investigation of palladium coverage on free air balls of palladium-coated copper wires | [35] | Collaboration works in China between Fudan University and ASE Assembly and Test (Shanghai) Limited. |
| Oxidation and corrosion of Au/Al and Cu/Al in wire bonding assembly   | [69] | Collaboration works in Singapore between ITE College Central and Promat Consultants.  |
| Comparison of Au/Al and Cu/Al in wirebonding assembly and reliability | [41] |                                                                                   |
| Investigation of palladium coverage on bonded balls of palladium-coated copper wires | [36] | Collaboration works in Singapore between Powertech Technology Inc., ITE College Central and Semicon Fine Wire Pte. Ltd.  |
| High temperature automotive application: A study on fine pitch Au and Cu WB integrity vs. Ni thickness of Ni/Pd/Au bond pad on C90 low k wafer technology | [40] | Collaboration works in 2 countries Malaysia and United States, whereby Freescale Semiconductor, (M) Sdn. Bhd., Freescale Semiconductor Inc., Corporate Headquarters, and Multi Media University.  |

Table 4. Collaboration works under keywords “corrosion” and “solder” in conference and journal from Scopus search engine.

| Title                                                                 | Authors | Remarks                                                                 |
|----------------------------------------------------------------------|---------|-------------------------------------------------------------------------|
| Electrochemical corrosion in electric energy meters                   | [44]    | Collaboration works in China between Southern Power Grid Science Research Institute Co. Ltd. Huazhong University of Science and Technology. |
| The morphology of Pb-free Sn-3.0Ag-0.5Cu solder reinforced by NiO nanoparticles | [70]    |                                                                                   |
| Effect of phosphorus and nickel on electrochemical migration of Sn-3Ag-0.7Cu solder paste in simulated body fluid | [71]    |                                                                                   |
| Electrochemical migration behaviours of low silver content solder alloy SAC 0307 on printed circuit boards (PCBs) in NaCl solution | [72]    |                                                                                   |
| Electrochemical migration behaviours of low silver content solder alloy SAC 0307 on printed circuit boards (PCBs) in NaCl solution | [72]    |                                                                                   |
| Investigation of electrochemical migration on Sn-0.7Cu-0.3Ag-0.03P-0.005Ni solder alloy in HNO3 solution | [73]    | Collaboration works in Malaysia between Universiti Kebangsaan Malaysia and Jabil Circuit Sdn. Bhd. |
| Investigation of corrosion on SAC 305, SAC 0307 and SAC 0307-0.03P-0.005Ni solder paste alloys in simulated body fluid (SBF)-Journal | [74]    |                                                                                   |
| Corrosion characterization of Sn-Zn solder: a review-Journal          | [75]    | Collaboration works in 2 countries Malaysia and Turkey between Universiti Malaysia Perlis, Universiti Sains Malaysia, Duzce University, Universiti Kebangsaan Malaysiaia, Universiti Malaysia Kelantan, and Jabil Circuit Sdn Bhd  |
| Electrochemical migration and corrosion behaviours of SAC305 reinforced by NiO, Fe2O3, TiO2 nanoparticles in NaCl solution | [76]    | Collaboration works in Malaysia between Universiti Kebangsaan Malaysia, Maktab Rendah Sains Mara Kuching, and Western Digital. |
| An investigation into the effect of dry bake on the solderability degradation of electrodeposited tin finishes | [46]    | Collaboration works in United Kingdom and China between Loughborough University, Leicestershire, and Huawei Technologies Co. Ltd. |
Table 4. Cont.

| Title                                                                 | Authors                                                                 | Remarks                                                                                                                                                                                                 |
|----------------------------------------------------------------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Accelerated SLID Bonding for Fine-Pitch Interconnects with Porous Microstructure | [77] Fraunhofer Institute for Reliability and Microintegration had collaborated between Universität Dresden and University Berlin.          |
| Influence of humidity on reliability of plastic packages            | [78]                                                                    |                                                                                                                                                                                                       |
| Corrosion investigations on lead-free solder alloys in MgCl₂ and NaCl solutions | [79]                                                                    |                                                                                                                                                                                                       |
| Corrosion investigations on lead-free micro-alloyed solder alloys used in electronics | [80]                                                                    | The authors from Budapest University of Technology and Economics and Institute for Materials Science and Technology were collaborated with Bay Zoltan Foundation.                                           |
| Electrochemical corrosion of sac alloys: A review—Journal Collaboration work in Hungary between Budapest University of Technology and Economics and Research Centre | [81]                                                                    |                                                                                                                                                                                                       |
| Failure analysis and case study of plastic encapsulated microelectronics | [50] Collaboration works in China between Testing Institute, Guangzhou and Peking University. |                                                                                                                                                                                                       |
| The degradation of multi-crystalline silicon solar cells after damp heat tests | [82] Korea Electronic Technology Institute had collaborated with Korea University and Sungkyunkwan University. |
| The effect of encapsulant discoloration and delamination on the electrical characteristics of photovoltaic module | [83] Collaboration works in China between China Academy of Space Technology and Harbin Institute of Technology. |
| Microstructure of Sn-1Ag-0.5Cu solder alloy bearing Fe under salt spray test | [84] Collaboration works in Malaysia between Universiti Malaya, Universiti Sains Malaysia and Malaysian Institute of Microelectronic Systems (MIMOS) Berhad. |
| The effect of moisture on the degradation mechanism of multi-crystalline silicon photovoltaic module | [85] Collaboration works in China between China Academy of Space Technology and Harbin Institute of Technology. |
| Research of reflow soldering on Al-SiC composite material and thick film ceramic substrates | [86] Collaboration works in China between Testing Institute, Guangzhou and Peking University. |
| The comparison on the corrosion resistance of different kinds of PCB surface finishing: OSP, LF HASL and ENIG | [86] Collaboration works in China between CERL Lab and PCB CE, Inventec Corporation (Taoyuan) and National Chiao Tung University. |
| Investigation of the oxidation process at the copper-solder interface with atomic force microscopy | [52] Budapest University of Technology and Economics had collaboration with Preclinical Imaging and Biomarker Center and National Institute for Materials Science, Tsukuba, Japan. |
| Tin whisker growth from Sn-Cu (0–5 wt%) surface finishes             | [87]                                                                    |                                                                                                                                                                                                       |
| Au-Ge based alloys for novel High-T Lead Free Solder materials—Fundamentals and applications | [88]                                                                    | Collaboration works in 3 countries between Switzerland, Italy and United Kingdom whereby Empa-Materials Science and Technology, National Research Council (CNR), Institute for Energetics and Interphases (IENI), University of Genova, Italy and University of Leeds. |
| Investigation of BGA crack issue in normal production line           | [89]                                                                    | Collaboration works in China between Huazhong University of Science and Technology and Flextronics Mobile and Consumer.                                                                               |
| Effect of soldering parameters on reaction kinetics and phase transformations of SAC 305 solder | [90]                                                                    | Collaboration works in United States between South Dakota School of Mines and Technology, and Radiance Technologies.                                                                                 |
| Stencil evaluation of ultra fine pitch solder paste printing process | [91]                                                                    | Collaboration works in China between Wistron Corp., and National Taipei University of Technology.                                                                                                         |
| Phase growth process of Sn-3.0Ag-0.5Cu solder joints under mechanical cyclic loading at the same temperature | [92]                                                                    | Collaboration works in Japan between Toyama Prefectural University, Imizu, Toyama Industrial Technology Center, and Cosel Co., Ltd.                                                                        |
| Application of phase growth approach to prediction of thermal fatigue crack initiation lifetime in SN-3.0AG-0.5CU solder joints | [93]                                                                    | Collaboration works in Japan between COSEL Co., Ltd., Machinery and Electronics Research Institute and Toyama Prefectural University.                                                               |
| Title                                                                 | Authors                                                                                           | Remarks                                                                                                                                 |
|----------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Corrosion behavior of Sn-based lead-free solder alloys: a review    | [94]                                                                                              | Collaboration works in China whereby North China University of Water Resources and Electric Power, Zhengzhou Research Institute of Mechanical Engineering, Zhengzhou, Harbin Institute of Technology, State Grid Henan Electric Power Company, Ministry of Water Resources. |
| Effect of micromorphology on corrosion and mechanical properties of SAC305 lead-free solders | [95]                                                                                              | Collaboration works in China between Tianjin University and Beijing Institute of Space Mechanics & Electricity.                         |
| Influence of cobalt content on microstructure and corrosion performance of extruded Sn-9Zn solder alloys | [96]                                                                                              | Collaboration works in China between Research Institute of Electronics and Technology, Central South University and Key Laboratory of Electronic Packaging and Advanced Functional Materials. |
| The effect of rare earths additions on the microstructure and the corrosion behavior of Sn-0.7Cu-0.075Al solder alloy | [97]                                                                                              | Collaboration works in China whereby Guangxi University and Shenzhen Academy of Inspection and Quarantine.                         |
| Morphology, resistivity and corrosion behavior of tin coatings plated from citric acid bath | [98]                                                                                              | Collaboration works in South Korean between Ajou University, Korea Institute of Industrial Technology, and Hanbat National University. |
| Research Status and Prospect of Au-based Medium-Low Temperature Filler Metals | [99]                                                                                              | Collaboration works in China between Nanjing University of Aeronautics and Astronautics, and Shanwei Source Advanced Materials Corporation. |
| Sliding Interconnection for Flexible Electronics with a Solution-Processed Diffusion Barrier against a Corrosive Liquid Metal | [100]                                                                                              | Collaboration works in China between Pukyong National University, Seoul National University of Science and Technology, Korea Institute of Energy Research. |
| Corrosion and Electrochemical Behavior of Sn-2Ag-0.5Cu Lead-Free Solders Solidified with Magnet Stirring | [101]                                                                                              | Collaboration works in Egypt between Zagazig University and Higher Technological Institute.                                    |
| Electrochemical Migration Behavior Of Sn-3.0Ag-0.5Cu Solder Alloy Under Thin Electrolyte Layers | [102]                                                                                              | Collaboration works in China between Huazhong University of Science and Technology, Sinopec Research Institute of Petroleum Engineering and Survey and Design Institute. |
| Correlation between microstructure and corrosion behaviour of Bi-Zn solder alloys | [103]                                                                                              | Collaboration works in Spain between University of Campinas and National Center for Metallurgical Research (CENIM-CSIC).         |
| Microstructural and damp-heat corrosion characteristics of Zn-2 wt%Al solder alloys containing trace Ag | [104]                                                                                              | Collaboration works in China between Zhengzhou University and Zhengzhou Research Institute of Mechanical Engineering.            |
| The effect of homogenization treatment on microstructure and properties of ZnAl15 solder | [105]                                                                                              |                                                                                                                                 |
| Microstructure and properties of Cu-Sn-Zn-TiO$_2$ nano-composite coatings on mild steel | [106]                                                                                              | Collaboration works in 2 countries China and United States between Jiangsu University of Science and Technology and Pacific Northwest National Laboratory. |
| Corrosion mechanism of Zn-30Sn high-temperature, lead-free solder in neutral NaCl solution | [107]                                                                                              | Tsinghua University had collaborated with Osaka University and China Ship Development and Design Center. Harima Chemicals, Inc. and Senju Metal Industry Co., Ltd. |
| Effects of Zn-bearing flux on joint reliability and microstructure of Sn-3.5Ag soldering on electroless Ni-Au surface finish | [108]                                                                                              |                                                                                                                                 |
| Electrochemical Behavior of Sn-9Zn-xTi Lead-Free Solders in Neutral 0.5M NaCl Solution | [109]                                                                                              | Collaboration works in China between China Ship Development and Design Center and Tsinghua University.                         |
| Effect of trace Mn modification on the microstructure and corrosion behavior of Sn-9Zn solder alloy | [110]                                                                                              | Collaboration works in China between China Ship Development and Design Center and Tsinghua University.                         |
| Title                                                                 | Authors                                                                 | Remarks                                                                                                                                                      |
|----------------------------------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hillock Sn whiskers growth behaviors in Sn-0.3Ag-0.7Cu/Cu solder joints during corrosion | [111]                                                                  | Chinese Academy of Science had collaborated with Jiangsu Normal University, Zhengzhou Research Institute of Mechanical Engineering, Institute of Metal Research, Shenzhen Huawei Technol. Inc. |
| Corrosion of Ga-doped Sn-0.7Cu solder in simulated marine atmosphere  | [105]                                                                  |                                                                                                 |                                                                                                                   |
| Ab initio surface properties of Ag-Sn alloys: Implications for lead-free soldering | [112]                                                                  | Collaboration works in 2 countries between and Ireland and China between College Dublin College Green and Nokia Bell Labs.                                           |
| Surface metallization of Cu/Ni/Au coatings on diamond/Cu composite materials for heat sink application | [113]                                                                  | Collaboration works in China between Hefei University of Technology and Guangdong University of Technology, Guangzhou and Hefei University of Technology and China Electronic Technology Group Corporation. |
| Corrosion behavior of Sn-3.0Ag-0.5Cu lead-free solder joints          | [114]                                                                  | This author had collaborated with 3 different industry such as Chinese Academy, US Environmental Protection Agency of Sciences and Senju Metal Industry Co., Ltd.       |
| In situ 2D maps of pH shifts across brass-lead galvanic joints using microelectrodes | [114]                                                                  |                                                                                                 |                                                                                                                   |
| Electrochemical behavior of Zn-xSn high-temperature solder alloys in 0.5 M NaCl solution | [114]                                                                  |                                                                                                 |                                                                                                                   |
| BGA substrate outgassing negative impact study on Cu wire bonding     | [59]                                                                   | Collaboration works in China between Tianjin University and NXP Semiconductor (China) Ltd.                                                              |
| The Effect of Substrate Microstructure on the Heat-Affected Zone Size in Sn-Zn Alloys Due to Adjoining Ni-Al Reactive Multilayer Foil Reaction | [115]                                                                  | Collaboration works in United States between University of Florida and Sandia National Laboratories.                                                         |
| Initial Corrosion Behavior and Mechanism of PCB–HASL in Typical Outdoor Environments in China | [116]                                                                  | Collaboration works in China between University of Science and Technology Beijing and Luoyang Ship Material Research Institute.                             |
| Distribution system water age can create premise plumbing corrosion hotspots | [117]                                                                  | Collaboration works in United States between Virginia Tech and Camp Dresser & McKee (CDM).                                                               |
| Effect of graphene nanosheets on the corrosion behavior of Sn–Ag–Cu solders | [118]                                                                  | Collaboration works in China and Singapore whereby Tianjin University and Singapore Institute of Manufacturing Technology.                                 |
| Investigation of Acetic Acid Corrosion Impact on Printed Solar Cell Contacts | [119]                                                                  | Collaboration works in Germany whereby Fraunhofer Institute for Solar Energy Systems and University of Freiburg.                                            |
| Effects of PCB Substrate Surface Finish, Flux, and Phosphorus Content on Ionic Contamination | [120]                                                                  | Collaboration works in Poland whereby University of Agriculture in Krakow—Agriculture and Economics, Foundry Research Institute—Center for High-Temperature Studies, and Fideltronik Imel. |
| Corrosion of laser joined silicon carbide in gasification environment  | [121]                                                                  | Collaboration works in Germany between Institute of Energy and Climate Research (IEK-2), Technische Universität Dresden, Institute of Power Engineering.       |
| A novel technique for the connection of ceramic and titanium implant components using glass solder bonding | [122]                                                                  | Collaboration works in Germany between University Medicine Rostock, Praxis fuer Zahnheilkunde, and ZM Praezisionsdentaltechnik GmbH.                         |
| Corrosion behavior of Sn-3.0Ag-0.5Cu solder under high-temperature and high-humidity condition | [123]                                                                  | Hebei Normal University had collaborated with Science and Technology and Chinese Academy of Sciences.                                                         |
| Effect of microstructure and Ag3Sn intermetallic compounds on corrosion behavior of Sn-3.0Ag-0.5Cu lead-free solder | [124]                                                                  |                                                                                                 |                                                                                                                   |
| Study on mitigation method of solder corrosion for crystalline silicon photovoltaic modules | [125]                                                                  | Collaboration works in 2 countries South Korea and Australia whereby Korea Electronic Technology Institut, University of New South Wales and Korea University. |
### Table 4. Cont.

| Title                                                                 | Authors                                                                 | Remarks                                                                 |
|----------------------------------------------------------------------|-------------------------------------------------------------------------|------------------------------------------------------------------------|
| Methods for predicting corrosion on electronic products               | Collaboration works in 2 countries Sweden and Denmark, whereby SP Technical Research Institute of Sweden, Jönköping University and SP Technical Research Institute of Sweden A/S. |
| Enhancement of interfacial reaction between solid iron and molten tin by mechanical actions | Toshiba Corporation, Toshiba Electronics Trading (Malaysia) Sdn. Bhd. and Furukawa Co., Ltd. had collaborated with Saitama University and Nagaoka University of Technology. |
| Creep-fatigue crack growth behavior of Pb-containing and Pb-free solders at room and elevated temperatures | Collaboration works in 2 countries China and Singapore, whereby Tianjin University, Tianjin Key Laboratory of Advanced Joining Technology and Singapore Institute of Manufacturing Technology. |
| Effect of Ni-coated carbon nanotubes on the corrosion behavior of Sn-Ag-Cu solder | Collaboration works in Taiwan between I-Shou University, and China Steel Corporation Kaohsiung. |
| The corrosion characteristics and solderability of immersion tin coatings on copper | Collaboration works in Poland between Tele and Radio Research Institute and Warsaw University of Technology. |
| Effect of thickness and phosphorus content on Au/Pd/Ni(P) metal finish of printed circuit board | Collaboration works in Philippines between Chung Yuan Christian University, OMG (Asia) Electronics Company Limited and Mapúa Institute of Technology Intramuros. |
| Effect of oxidation on whisker growth in RE-containing lead-free solder | Collaboration works in China between Nanjing University of Aeronautics and Astronautics and Zhengzhou Research Institute of Mechanical Engineering. |
| A comparison of corrosion behavior of a super duplex stainless steel and an austenitic stainless steel in a molten Sn-3.0Ag-0.5Cu lead-free solder | Collaboration works in Taiwan between National Yunlin University of Science and Technology (NYUST) and CPC Corporation. |
| The role of elastic and plastic anisotropy of Sn in recrystallization and damage evolution during thermal cycling in SAC305 solder joints | Collaboration works in Japan between Hyogo Prefectural Institute of Technology, Ritsumeikan University and KYOCERA SLC Technologies Corporation. |
| Correlation between Sn grain orientation and corrosion in Sn-Ag-Cu solder interconnects | Collaboration works in United States between State University (Virginia Tech) and URS Corporation. |
| Notch effect on creep-fatigue life for Sn-3.5Ag solder | Collaboration works in United States between the industry and academia showed the main author of these paper from Andong National University had collaborated with Electronics and Telecommunications Research Institute, Pohang Institute of Metal Industry Advancement, Advanced Welding and Joining Technology Center, KITECH, JESAGI HANKOOK Ltd. |
| The study on defects of 6-inch cylinder by electromagnetic acoustic transducer (EMAT) | Collaboration works in Taiwan between National Yunlin University of Science and Technology (NYUST) and CPC Corporation. |
| Chloride-to-sulfate mass ratio: Practical studies in galvanic corrosion of lead solder | Collaboration works in United States between State University (Virginia Tech) and URS Corporation. |
| Influence of electrochemical properties on electrochemical migration of SnPb and SnBi solders | Collaboration works in United States between the industry and academia showed the main author of these paper from Andong National University had collaborated with Electronics and Telecommunications Research Institute, Pohang Institute of Metal Industry Advancement, Advanced Welding and Joining Technology Center, KITECH, JESAGI HANKOOK Ltd. |
| Elucidation of the relationship between the electrochemical migration susceptibility of SnPb solders for PCBs and the composition of the resulting dendrites | Collaboration works in United States between the industry and academia showed the main author of these paper from Andong National University had collaborated with Electronics and Telecommunications Research Institute, Pohang Institute of Metal Industry Advancement, Advanced Welding and Joining Technology Center, KITECH, JESAGI HANKOOK Ltd. |
| Solder joint properties of Sn-Ag-Cu solders on environmental-friendly plasma surface finish | Collaboration works in United States between the industry and academia showed the main author of these paper from Andong National University had collaborated with Electronics and Telecommunications Research Institute, Pohang Institute of Metal Industry Advancement, Advanced Welding and Joining Technology Center, KITECH, JESAGI HANKOOK Ltd. |
| Directional diffusion of atoms in metal strips/bump interconnects of flip chip | Collaboration works in United States between the industry and academia showed the main author of these paper from Andong National University had collaborated with Electronics and Telecommunications Research Institute, Pohang Institute of Metal Industry Advancement, Advanced Welding and Joining Technology Center, KITECH, JESAGI HANKOOK Ltd. |
| Effect of Ag addition on the properties of Sn-1.5Zn based alloys for soldering aluminum | Collaboration works in United States between the industry and academia showed the main author of these paper from Andong National University had collaborated with Electronics and Telecommunications Research Institute, Pohang Institute of Metal Industry Advancement, Advanced Welding and Joining Technology Center, KITECH, JESAGI HANKOOK Ltd. |
| Effect of aluminum addition on the microstructure and properties of non-eutectic Sn-20Bi solder alloys | Collaboration works in United States between the industry and academia showed the main author of these paper from Andong National University had collaborated with Electronics and Telecommunications Research Institute, Pohang Institute of Metal Industry Advancement, Advanced Welding and Joining Technology Center, KITECH, JESAGI HANKOOK Ltd. |
| Impact of key deposition parameters on the voiding sporadically occurring in solder joints with electroplated copper | Collaboration works in United States between the industry and academia showed the main author of these paper from Andong National University had collaborated with Electronics and Telecommunications Research Institute, Pohang Institute of Metal Industry Advancement, Advanced Welding and Joining Technology Center, KITECH, JESAGI HANKOOK Ltd. |

Figure 24 shown the total number collaborative work in from IEEE and Scopus for 2010 to 2020. It is observed that the collaborative works tend to publish in Scopus as compared to IEEE. Since 2010, the trend collaborative works among the industry and academia showed
increasing from total of 13 in IEEE and Scopus and become to 165 total publications in 2020. This shows that a significant increase in collaboration works from industry and academia. Research institutions are categorized as industry is due to the research institute having business like industry and they develop their own technology such as intellectual property (IP), processing and products. Research institutes also have a linkage with academia and government sector in terms of research and development. Meanwhile research activities by academia are slightly different with research institutes whereby the research activities are put together with the education and scholar activities. This is the reason why the research activities in academia need to produce technical publications and the backbone of the research activities are from students, research assistants and research fellows. The industry is very likely shows their work in conference platform to broadcast their work. This is somewhat distinct from academia because the industry gives less attention to fundamental aspects. The industries are more presents technical as compared to fundamental point of view. From the data collected from Scopus and IEEE search engine for all types of combined keywords, it is found that the industry is prone to report their work in industrial-based platform, which dominated by IEEE. While academia published both in journal and conference in Scopus and IEEE platforms. The industry is susceptible to IEEE platform because the IEEE is the biggest organization in E&E and have very strong technical society and council. There is specific societies in IEEE such as IEEE electronics packaging society (EPS), IEEE electron devices society (EDS), IEEE industrial electronics society (IEE), IEEE reliability society etc. These societies are dedicated to their technical interest, networking, collaboration research projects on their area of expertise. Typically, academicians submit their research work for journal publications in IEEE and Scopus. They also present their work in conferences to broaden their networking. Meanwhile collaborative work between the academia and industry will look on the detailed findings of the research work. The industry usually provides technical details on the research work while the academia give input from the fundamental point of view. Collaborative publications have incorporated the academia and industrial practices perspective.

![Total number collaborative work in from IEEE and Scopus for 2010 to 2020.](image)

**Figure 24.** Total number collaborative work in from IEEE and Scopus for 2010 to 2020.

The publications of keywords corrosion and wire bonding has dominated by publication in conference as compared to journal (Figure 5). It is also found that the collaborative publication in conference is higher than journal publications. This is due to the wire bonding as interconnection materials in electronic packaging have been widely used and reported. The evolution from gold wire bonding to the Cu and Al wire bonding has attracted the interest of electronic industry. The wire bonding has already been established,
and for specific application of the electronic package, the corrosion issue has become the biggest concern. The wire bonding corrosion typically occurred inside the encapsulation. However, Au still being used as wire bonding materials and the leadframe is made from Cu. For normal applications of electronic packaging, the corrosion issue does not become concern as compared to harsh applications such as in automotive. The corrosion issue in wire bonding and leadframe will lead to catastrophic failure. This can be seen from Figure 7 as very minor publications regarding leadframe and corrosion from industry. For keywords of corrosion and solder, it is involved in alloy development. So that there are many publications regarding from these keywords on the corrosion properties of the solder materials. The development of new solder materials usually involved characterization of the materials including the corrosion properties.

4. Conclusions

In summary, there are many works on corrosion issues in electronic packaging from 2010 until 2020. The corrosion aspect of electronic packaging is mainly related to metallic materials such as wire bonding, leadframe, and solder. Electronic packaging has become research interest for both academia and industry. According to our analysis, on our premise of IEEE and scopus, is if found that for keywords corrosion and wire bonding, the industry prone to publish conference paper in IEEE while academia published more in journal publications in Scopus. It was found that the conference publication is higher that journal publication for collaborative work. For keywords corrosion and leadframe, the academia published journal and conference in IEEE, while industry only published conference paper in Scopus. There is no collaboration work between academia and industry for keywords corrosion and leadframe. For keywords corrosion and solder, both academia and industry published more conference as compared to journal in IEEE. Academia published more journals in Scopus as compared to industry. Only conference paper published in IEEE from the collaborative work for keywords corrosion and solder while more journal than conference publications for collaborative work in Scopus.

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