

## 전기해체 접착제

정종구<sup>†</sup>

히가시야마 필름

(2018년 06월 08일 접수, 2018년 06월 11일 수정, 2018년 06월 13일 채택)

### A review on electrically debonding Adhesives

Jongkoo Jeong<sup>†</sup>

Higashiyama Film co., 1, 2460 Kanenawate Nakashidami Moriyama-ku Nagoya, 463-0002, Japan

(Received June 08, 2018; Revised June 11, 2018; Accepted Jun 13, 2018)

**Abstract:** Electrically debonding adhesives[EDA], one of the controlled delamination materials[CDM] is reviewed. CDM can be defined as the ability to separate adhesive bonded assemblies without causing damage to the substrates. Its application includes electronics, medical surgery, dentistry, building and general manufacturing where the opportunity to separate assemblies is important. There are several important mechanisms of EDAs; faradaic reaction, phase separation and anode detachment, cathodic debonding, gas emission mechanism, and mechanical stresses. These mechanisms are reviewed with various research results. Since the mechanism behind the electrochemical debonding of adhesives is not well understood, this review aims to help the research scientists in the industries. Finally, new applications of EDA are introduced as new business opportunity.

**Keywords:** water primer, adhesion, peel strength, toluene-free

### 1. Introduction

Electrically debonding adhesives[EDA] is one of the controlled delamination materials[CDM]. The definition of CDM is the ability to separate adhesive bonded assemblies without causing damage to the substrates. The application of CDMs includes electronics, medical surgery, dentistry, building and general manufacturing where the opportunity to separate assemblies is important. Thus CDM is needed for repositioning in manufacturing, reuse, repair in service or recovery of materials at end of life, say, 3R.

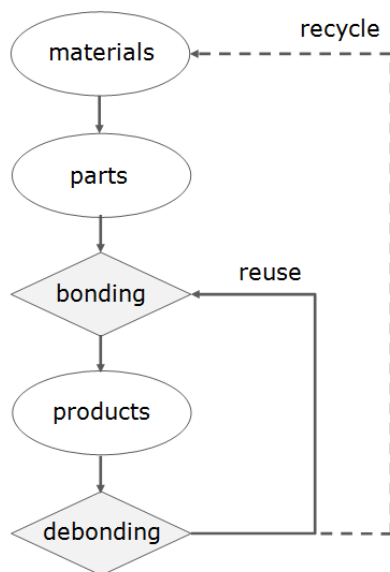
Various technologies for adhesive reversibility or debonding have been developed over the last 40 years but there seems to be no universally accepted solutions for CDM applications. [1] Since the mechanism behind the electrochemical debonding of adhesives is not well understood, this review aims to fill some of those gaps, for the research scientists in the industries.

Several important mechanisms have been proposed; faradaic reaction, phase separation and anode detachment, cathodic debonding, gas emission mechanism, and mechanical stresses.

Electrically induced adhesive debonding is a concept which could potentially be used in a wide range of applications, such as light-weight automotives, which can be easily recyclable at the touch of a button. The technology of electrically assisted delamination has potential applications in many fields, such as easy-to-open consumer packaging and recycling of lightweight materials.

A better understanding about the mechanisms leading to debonding is important for further development of the technique, and is one of the goals of this review.

<sup>†</sup> Corresponding author: Jongkoo Jeong (jeong@hynt.co.jp)



**Figure 1.** The concept of 3R in the industries: reuse, repair in service or recovery of materials at end of life.

Another goal, in the context of non-structural and structural joints, is to summarize the target of CDMs, the requirements and considerations associated with possible technologies, and the mechanisms along with the associated methods for activation, thus providing the researchers of historical and theoretical backgrounds. It is clearly desirable that a total materials system approach must be adopted when seeking a disbonding technology for a particular set of circumstances.

It is worthwhile to note keywords for CDM system, since its terminology differs for every failure mode and phenomenon.

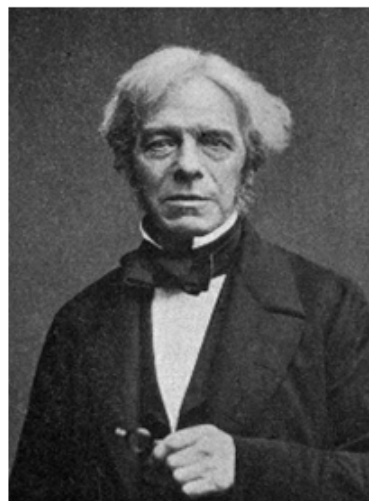
Keywords: electrically, electrochemically, peeling, peelable, disbonding, debonding, dismantling, adhesives, materials, controlled delamination material [CDM], debonding on demand [DoD], releasing on command, [通電/電壓/電氣] & [剝離性/剝離型] & [接着劑/組成物].

## 2. Proposed mechanisms

### 2.1. Faradaic reaction

Michael Faraday(1791-1867) was an English scientist who contributed to the study of electromagnetism and electrochemistry. circa 1861.

As he proposed, Faradaic process can be defined as current flow as a result of electron transfer (charge



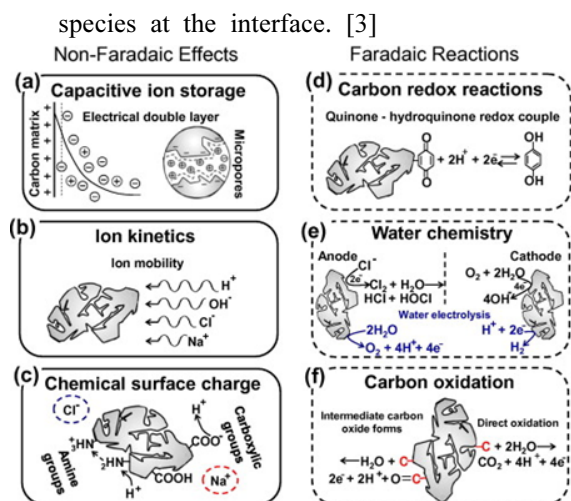
**Figure 2.** Michael Faraday (1791-1867) circa 1861. Opposite p. 290 of Millikan and Gale's Practical Physics (1922).

transfer, redox reaction). There is another electrode process, non-Faradaic process, which means the current flow as a result of the capacitive nature of an electrode. This is termed the double layer capacitance, CDL. These two electrode processes can be seen graphically in Fig. 3.

### *The functionality:*

The functionality that the EDAs possess is a functionality of cohesive strength and adhesion, and an electrolyte functionality which provides sufficient ionic conductivity to support faradaic reactions. Gilbert suggested that the faradaic reactions occur at interfaces of the adhesive and conductive substrates during electrical debonding, as evidenced by the establishment of an ionic current. [3] Hence the contribution of faradaic reactions to the weakening of the adhesive bond can be summarized as:

- (1) Electrochemical degradation of the adhesive composition, or dismantling
- (2) Digestion of the electrically conducting substrate
- (3) Generation by faradaic reactions of corrosive species that degrade the composition or substrate
- (4) Ionic flow or the establishment of an electric field
- (5) Dewetting of the composition from the electrically conductive substrate
- (6) Generation of gaseous products at the interface
- (7) Transport and accumulation of liquids and other mobile species at the interface
- (8) Accumulation of ions, solvents or other mobile



**Figure 3.** Overview of important electrochemical reactions and processes in CDL electrodes. [2]

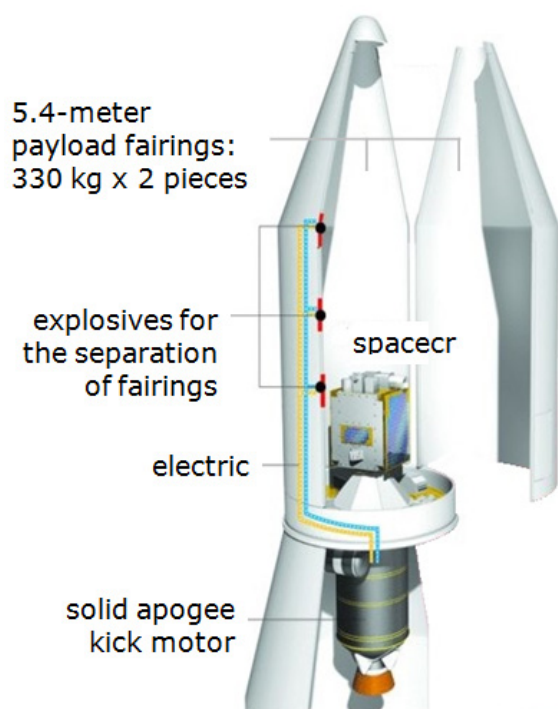
First need of CDM(controlled delamination material) was from the U.S. Air Force in the early 2000s.

The requirements for such adhesive were (1) to be used for attaching test packages to the exterior of a jet without mechanical fasteners, (2) to bond packages, each weighing a few pounds, (3) to withstand Mach 2 flight, and (4) to remove the packages without damaging them or marring the paint on the jet. EIC Laboratories Inc. (Norwood, MA)'s ElectRelease was developed to meet the requirements. The new high-strength adhesive is a two-part, amine-cured epoxy, and debonds from a metal surface when an electrical current passes across the epoxy-metal interface, at a typical voltage 10 to 50 VDC (a current flow of less than 1 mA/square inch of bond line).

#### **Debonding process:**

As electrical current, in the form of ions, flows through the epoxy during disbonding, electrochemical reactions occur at both the positive and negative interfaces between the adhesive and the conductive substrates.

The parts separate at the positive interface(anode) without mechanical, thermal or chemical damage. However, the electrochemical reactions at the negative interface do not cause disbonding. Although it is not necessary to use a metal as the negative substrate, it must conduct electrons. For example, carbon-fiber reinforced epoxy composites are suitable negative substrates. If two metal substrates are bonded, disbonding at both interfaces is possible by reversing the polarity of the disbonding



**Figure 4.** The first Korean spacecraft, Naro KSLV-1 (Korea Space Launch Vehicle-I), exploded in the space on August 25, (2009).

voltage. To bond nonconductive materials or painted surfaces, EIC developed an ElectRelease foil patch. The patch consists of two sheets of metal foil, usually aluminum, laminated with a thin layer of precured ElectRelease. The patches are cut to shape, and any standard adhesive is applied to each surface. The nonmetallic parts are then bonded with the adhesive-coated patch. The parts are debonded by applying a voltage between the two metal foils. The bond separates at the interface between the ElectRelease and the positive foil.

#### **Faradaic reaction of EDA for spacecraft:**

The first Korean spacecraft, Naro KSLV-1(Korea Space Launch Vehicle-I), exploded in the space on August 25, 2009. The investigation team announced that one of the payload fairings seemed not to be separated properly. The fairings should be separated away before the spacecraft is separated. (Fig. 4)

Present separation system worldwide is the pyrotechnically driven separation system. The system has been proven to be acceptably reliable, however, it has the primary disadvantages of relatively massive and generating significant pyroshock when activated. As a

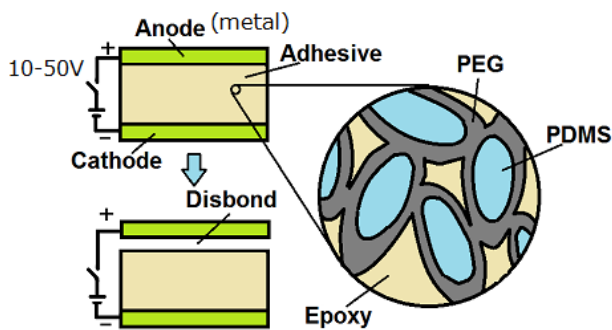


Figure 5. Microscopic structure of EDA, upon curing. [6]

result, additional expense is associated with these systems to minimize the safety hazards associated with these systems.

For the development of faring and payload release device, the requirements are lightweight, reliable, economical separation systems. Also the recent trend is towards the integration of non-explosive release devices, and EDA system has the reduced safety efforts, reduced weight, and no pyroshock. [4]

## 2.2. Anode detachment and phase separation

### Phase separation:

ElectRelease, developed by EIC Laboratories, is one of the most prominent and elaborate systems to date. In the adhesive system, pseudo-micelles are formed by incorporating a nanoscaled backbone blocks of PDMS into a two-part amine-cured epoxy resin structure. The backbone structure is also attached to the arms of PEG which creates a comb-type polymer and pseudo-micelles structure in the uncured epoxy resin. Phase separation occurs upon curing. The PEG micelle phase separates from the epoxy around the immiscible PDMS cores and forms a nanoscaled co-continuous network, Fig. 5. [5]

Berg et al. developed a remote-activation locks designed to permit unlocking and/or locking of the lock utilizing EDA, and suggested the phase separation mechanism using a polymer blend system. [7] An energy-releasable structure was developed comprising: (1) an adhesive mixture comprising at least one polar polymer and at least one non-polar polymer, which are substantially uniformly dispersed throughout the adhesive base, (2) non-polar polymer was selected from silicone polyols or isocyanate-terminated polybutadienes, and (3) an electrically conductive material, such as conductive

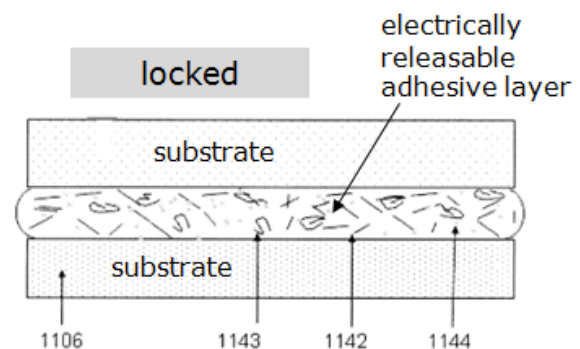


Figure 22A: A cross-sectional schematic view of an embodiment of an electrically releasable adhesive system with no applied voltage across the two substrates

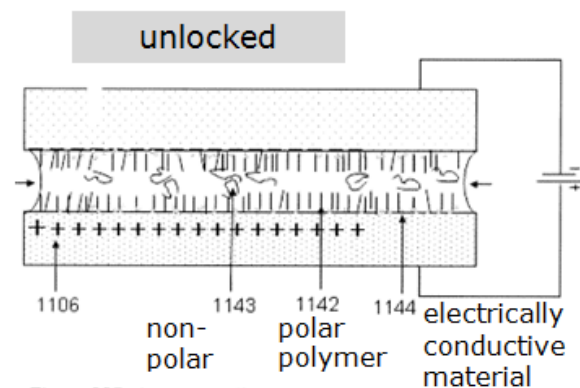


Figure 22B: A cross-sectional schematic view of an embodiment of an electrically releasable adhesive system with an applied voltage across the two substrates

Figure 6. Phase separation mechanism in EDA. [7]

salts, metal particles, metal wires, nanowires, and carbon nanotubes, was uniformly dispersed throughout the adhesive base. When the system was triggered by a transmitted specific profile of energy, such as magnetic, electrical, electromagnetic, acoustic, light, and heat, then the adhesive mixture could transition from a first physiochemical state to a second physiochemical state, see Fig. 6.

### Anode detachment:

The debonding occurs by the ion conduction along the resin-metal interface. The structural epoxy adhesive is electrically quite easily separated at anode by applying an electric current at 10-50V, the current  $< 1 \text{ mA/in}^2$ , in a few seconds ~ minutes. The ionic conductivity determines the effectiveness of the disassembly process. Epoxy resins normally have a relatively low ionic conductivity. Since high ionic conductivity polymers are typically in a rubbery or gel-like state, a nano-scaled block copolymer

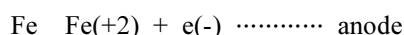
is added to modify the ionic conductivity. [8] High level ionic conductivity can be further achieved through post-treatment with suitable salts. [6]

The debonding needs a metal as the positive substrate and another suitable material for the negative substrate. When two metal substrates are bonded -using ElectRelease, debonding at both interfaces can be achieved by reversing the polarity of the debonding voltage. For non-conductive materials, an ElectRelease foil patch (EFP) which is essentially two sheets of metal foil, is applied on the surface to enable electric conductivity. [9]

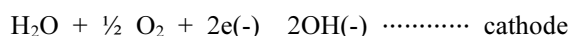
### 2.3. Mechanism of cathodic debonding

In contrast to anode detachment, a mechanism of cathodic debonding is attributed to an adhesive joints failure in an aqueous environment. Cathodic debonding or delamination occurs when failure of an organic coating is associated with a cathodic potential on metal surfaces. Such a potential may emanate from the electrolytic cell that exists at the surface of a corroding metal, or by an impressed potential from outside.

In the case of corroding steel, the anodic reaction leads to a rust on the surface:



The electrons are consumed in the cathodic reaction which involves oxygen and water, producing hydroxyl ions. Hydroxyl ions in turn increase the pH of electrolyte at the coating/substrate interface.



The rate controlling step may be the diffusion of water. The hydroxyl group is eventually responsible for the adhesive failure of coatings and adhesive joints and Watts gave it the term cathodic disbondment. [10]

However, the failure also depends upon polymer, substrate and exposure conditions.

In the case of impressing cathodic potential of 1.0 ~ 1.5 V to the coated panel to a zinc electrode, cathodic disbondment of coatings can be observed too. The results show that the extent of disbondment from the metal is a function of time.

Classical mode of failure by cathodic disbondment: Interfacial bonding is attacked by alkali, resulting in the

failure of interfacial separation. Then failure occurs without any traces of polymers remaining behind. If failure does not occur at the interface, it may occur within the interfacial region of the polymer, leaving a very thin (< 5nm) polymer residue. Based upon the mechanism of cathodic debonding, conductive organic material is added in the polymer, in the case of EDA.

### Generation of hydrogen:

In 1956, Dorst [11] discovered that adherent resin layers may be removed from underlying bases by an electrolytic process in which the base metal is made of the cathode in an electrolytic cell.

When hydrogen was generated, and due to the confining action of the base metal and the impervious dielectric film, the hydrogen built up appreciable pressure. Then the insulating film layer was forced off the base metal by the pressure of gaseous hydrogen at the interface between metal and insulation.

In 1996, Keller et al. patented the technology of electrolytically assisted paint removal from a metal surface. They believed that the separation or debonding of the paint from the metal surface is primarily chemical in nature.

The cathodic reaction such as hydrogen evolution causes a localized higher pH which reacts to debond the coating, or to delaminate the paint. [12] Thus they suggested that paint removal from metal parts, relates to electrolytically assisted removal of paint from large structures such as bridge structures, tanks, ships, airplanes, automobiles and the like.

In 2001, Bushman and Jackson [13] also investigated the removal of lead-based paint from metal bridges, using an external electrolyte and an applied potential over the electrolyte and the paint. The density of the current was initially 1,000 A/m<sup>2</sup>. Especially during initial removal of

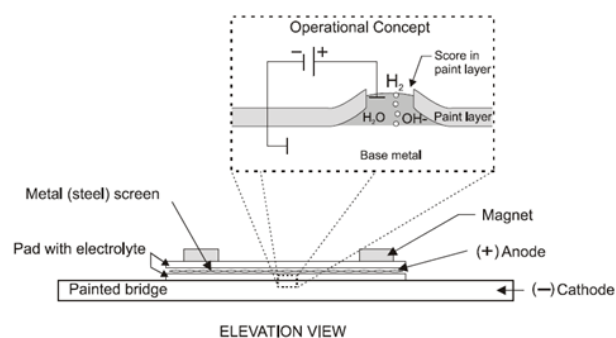


Figure 7. ElectroStrip Process.

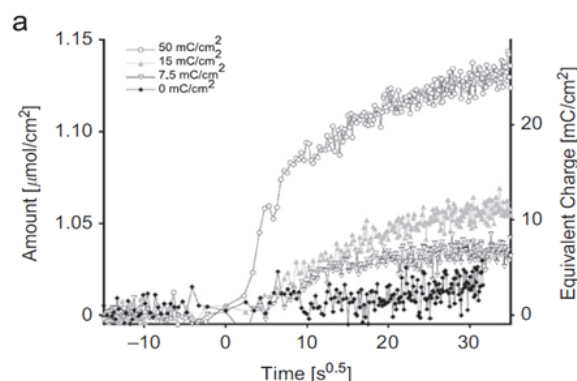
paint, there were loud, rapid detonations of, apparently, hydrogen offgassing as the reaction progressed, Fig. 7.

Leijonmarck et al. [14] also investigated the hydrogen evolution, which stemmed from an electrochemical reaction. They reported electrical debonding of a functional epoxy-based adhesive, applied between two aluminum foils, using electrochemical technique.

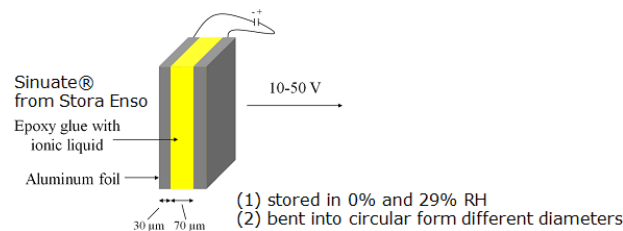
Debonding occurred at the anodic adhesive boundary, which became acidic during polarization. The reactions during polarization of the laminates consisted of two steps, with aluminum oxide/hydroxide formation as the first and the build-up of a sulfur rich organic film as the second. On the other hand, the dominating cathodic reaction was hydrogen gas evolution, Fig. 8. The amount of hydrogen gas released from the samples was within a factor 2 of the charges passed before the tearing of the laminates. The hydrogen gas created bubbles, visible in a light microscope, for charge densities over 50 mC/cm<sup>2</sup>.

#### 2.4. Mechanism of cathodic debonding

The development of EDA technology has triggered intense interest in investigating the mechanism. Leijonmarck found the emission of volatile species at anode. [15] The investigation was made on the electrically assisted debonding adhesive technology and provided further understanding of its mechanisms. A delamination process at the interface between the aluminum anode and the adhesive layer was observed, detecting the changes in polymer chemistry. And also the emission of volatile species was analyzed using mass spectrometry.



**Figure 8.** Amount of H<sub>2</sub> produced. Time 0 corresponds to when the aluminum foil was torn off. The second y-axis in the figure shows the amount of H<sub>2</sub> transformed to charge density, assuming that 2 electrons are consumed for every H<sub>2</sub> molecule formed.



**Figure 9.** Experimental scheme.

Sika Technology Ag. [16] detailed the incorporation of carboxylic acid hydrazides in polyurethane adhesives, where the gases coming out of the decomposition of hydrazides weaken the adhesion strength. The additive was especially selected from the group consisting of oxalic acid dihydrazide, adipic acid dihydrazide, azelaic acid, sebacic acid dihydrazide and isophthalic acid dihydrazide. When the adhesive is heated to a temperature of at least 80°C, the polymer is thermally broken down. Such an adhesive has the advantage that components thereby adhered can be released in a simple method, wherein the repair, reclamation, or recycling of the components is made easier.

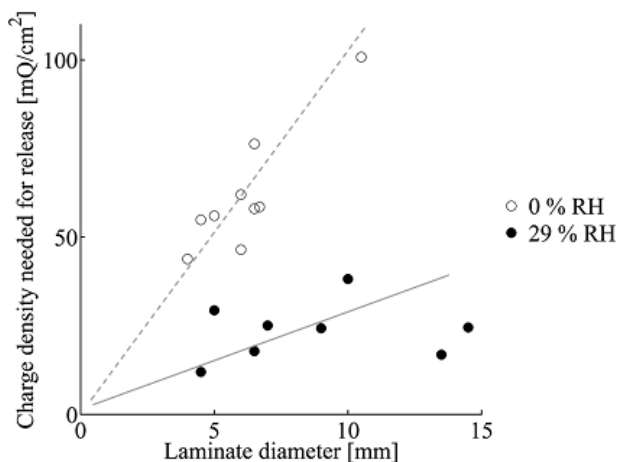
Rescoll Research Company's INDARTM Inside® [17] also added hydrazides such as para toluene sulphonyl hydrazide, which is a chemical blowing agent for polymers.

#### 2.5. Mechanism of cathodic debonding

Van Ooij et al. [18] used a model where the corrosion products at the galvanized steel/paint interface caused lateral stresses leading to delamination. Leijonmarck et al. [19] studied the controlled debonding of adhesive generated with electricity. An electrochemical investigation of debonding adhesives was performed using a laminate with an epoxy adhesive bonded between aluminum foils. It may be worthwhile to introduce one of the EDA recipes in this review for better understanding. They prepared an adhesive mixture by mixing:

73.4wt% epoxy resin, 2.3% dicyandiamide as curing agent, 0.125% n2-methylimidazole as accelerator, 18.5% 1-Ethyl-3-methylimidazoliumethylsulfate ionic liquid, 5.5% PEG 400, 0.5% Gransurf 77, before being cured between two aluminum foils.

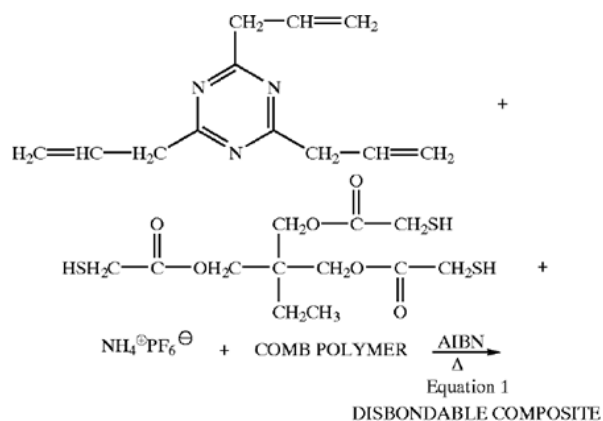
It was found that the resistance at the debonding anodic interface of the laminate increased during polarization. This increase in resistance was shown to be



**Figure 10.** Charge density needed for self-debonding with the anodic side bent inwards at different diameters. Current density=0.050 mA/cm<sup>2</sup>.

reversible at open circuit. During the polarization, aluminum compounds were produced at the anode. These compounds grew to penetrate the adhesive.

Laminates, stored in 0 and 29% RH, were bent into a circular form with different diameters, and then polarized. The laminates were bent onto cylinders of various diameters, thus changing the magnitude of imposed stress to the Al/adhesive interface. The charge density needed for debonding was found to depend on the water content of the adhesive, implying that the presence moisture gives debonding at low charge density. The charge density needed for debonding was found to depend on the imposed stress. The laminates, bent at a small diameter with large stress, needed less charge density for debonding, Fig. 9 and Fig. 10. [19]



**Figure 11.** Synthesis of debonding composite.

### 3. EDA Technologies

#### 3.1. Electrically assisted debonding

ElectRelease™ was developed by EIC lab. It has high strength bonding properties that can be completely and easily removed at a later time. Conductive (metallic) assemblies can be held together very strongly but then disassembled by applying a small amount of electricity. The electrical current causes a chemical reaction to release the bonds between the epoxy and one of the metal substrates, at anode. [20] Its release is predictable and highly efficient.

Application conditions are announced for 2 parts aliphatic amine cured epoxy-based debondable adhesive. Curing conditions are 1 hour at 80°C or 24 hours at room temperature. Debonding occurs with 10 V d.c. or greater, in 1 second or longer. Pot-life is 40 minutes for a 100 cc quantity that roll-to-roll converters need to develop their own coating machines. Typical uses include both temporary and permanent bonding applications.

- (1) Structures and appliances can be bonded and easily disassembled for re-use and recycling of components.
- (2) Inexpensive single-use remote release devices can be fabricated. These devices can be lightweight, mechanically robust and capable of holding large loads.
- (3) The adhesive can be used to bond nonconducting surfaces.
- (4) The adhesive is suitable for a variety of applications in aerospace, automotive, shipbuilding, defense, and other manufacturing.

#### Polymer structure:

The polymer structure of electrically debonding materials can be found in the patents of EIC Lab. [21] Admixtures of a comb polymer with monomers of thiols and trienes according to Fig. 11 would also yield a homogeneous mixture. Free radical polymerization with AIBN would result in network polymer formation and phase separation of the comb polymer.

In the adhesive, the matrix provides a bond to a substrate, and the electrolyte provides sufficient ionic conductivity and ion mobility needed to maintain the faradaic reaction at an interface with an electrically conductive surface in contact with the composition. An application of an electrical potential across the interface

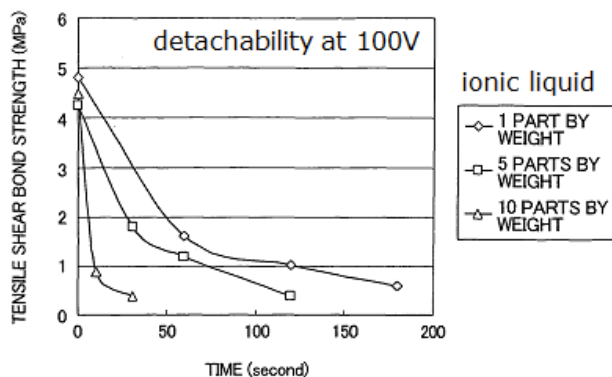
causes a faradaic reaction at the surface. The debondable composition undergoes a phase separation, having first regions of substantially matrix functionality and second regions of substantially electrolyte functionality. The adhesive bond is weakened at the interface resulting in debonding.

#### **Electrical treatment conditions:**

Studies on the electrical treatment conditions of EDAs have been made extensively at the universities in Japan. Shiote, Sato and Ohe investigated the effects of electrical treatment conditions on dismantable properties of joints with an electrically disbanding adhesive from EIC Lab. [6] The residual adhesion strength, after applying electric current, depends upon the charge density rather than applied voltage. Shiote et al. investigated further about the separation of an electrically dismantable adhesive. [22] It was found that the residual strength of a joint does not depend significantly on the bonding area but on the type of adherent material. The residual strength could be predicted by using charge density. Higher applied voltage was able to accelerate the decay of the residual strength and shorten the time for a given decrease in strength. The constant current application also induced a decrease in joint strength, which also corresponded to the total charge that could easily be calculated from duration for current application.

#### **3.2. Practical technology and compositions**

For electrically disbonding materials, the adhesive bond is weakened at the interface. The composition may be a phase-separated composition having first regions of substantially matrix functionality and second regions of substantially electrolyte functionality. The composition



**Figure 12.** Effect of ionic liquid upon adhesion strength.

can support a faradaic reaction with the electrically conductive surface, the faradaic reaction weakening the adhesive bond, wherein the electrolyte is provided by a block copolymer or a graft copolymer [21] Such compositions can be used in both temporary and permanent bonding and coating applications. [23]

Stora Enso Ab investigated a laminate structure utilizing electrochemically weak adhesive. They prepared the components in accordance with epoxy resin 77.95 wt%, EMIM-ES 19.0 wt%, diacynidamide hardener 2.86 wt%, and 2-methylimidazole accelerator: 0.19 wt%. [24] They also investigated the composition which includes particles and/or fibers enabling the formation of co-continuous networks of ion conducting channels in the composition. The particle size is within the range of 100 nm to 10  $\mu$ m. [25]

For EDAs, many kinds of polymers were studied such as PU hot melt. [26] An ionic liquid was studied to provide an electropeeling composition. [27] When the ionic liquid was increased from 1 wt% to 10 wt%, the decrease of the tensile bond strength became much faster, Fig. 12.

## **4. New applications of EDA**

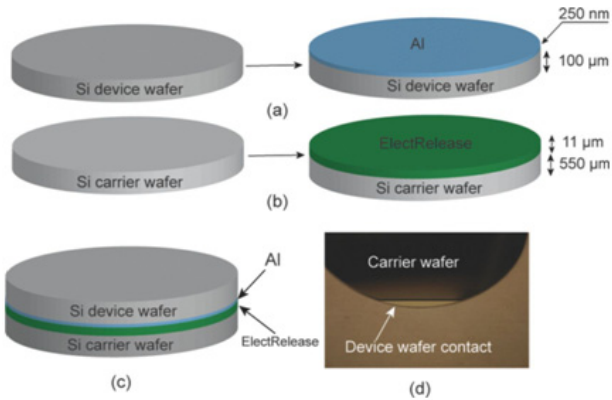
### **4.1. Temporary wafer bonding**

Thin silicon wafers, enabling technology for 3D integration in the semiconductor industry, are fragile to handle and reliable solutions are required for thin wafer handling.

Gatty et al. [28] reported a novel method of temporary wafer bonding using electrochemically active adhesives, which has the potential to be an attractive approach for thin wafer (<50  $\mu$ m) handling. The carrier wafer was first spin coated with the adhesive and then bonded to the device wafer by applying force and temperature. Debonding of the wafer was realized at room temperature by applying a voltage between the carrier and the device wafer, which substantially reduced the bond strength, see Fig. 13. and Fig. 14.

- Metal deposition on the device wafer.
- Spin coating on the carrier wafer with ElectRelease adhesive.
- Illustration showing the arrangement of the wafer stack after adhesive bonding of the aluminum coated device wafer.
- Photograph of the bonded stack showing the electrical contact area of the device wafer which is exposed at the carrier wafer flat. [28]





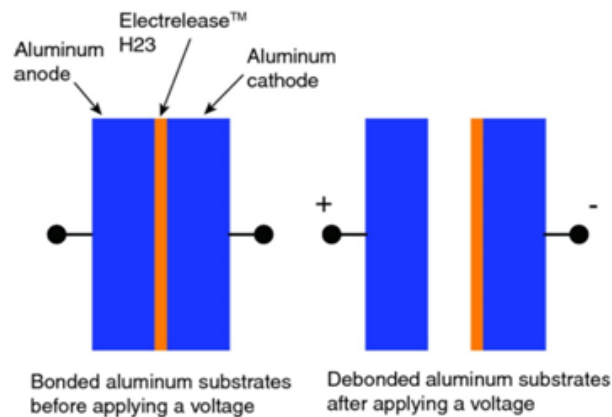
**Figure 13.** Illustration of the fabrication process flow for bonding a device wafer to a carrier wafer with ElectRelease electrochemical polymer adhesive for the first type of stack.

**4.2. Combination of RFID with EDA**

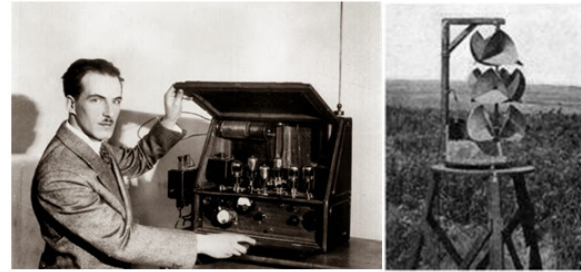
Russian physicist Leon Theremin is commonly attributed as having created the first RFID device in 1946. RFID technology was invented in 1948 by Harry Stockman, RFID is a kind of automatic identification technologies, Fig. 15.

In 1948, Harry Stockman published a legendary paper “Communication by Means of Reflected Power”, which is considered as the birth of RFID. He predicted that “... considerable research and development work has to be done before the remaining basic problems in reflected-power communication are solved, and before the field of useful applications is explored.” [29]

EDA technology was first used in aerospace applications to temporarily bond monitoring instruments to aircrafts, and permitting dismantling quickly without



**Figure 14.** Illustration of the debonding technique using the ElectRelease H23 adhesive. [28]



Stockman's Triple Turret Reflector

**Figure 15.** Russian physicist Leon Theremin is commonly attributed as having created the first RFID device in 1946.(left) and Harry Stockman’s triple turret reflector.

surface damage or marking. Using EDA, the conductor/ adhesive joint can be easily opened by applying a little electric power on to the material. The strong adhesion can support a lap of shear strength in excess of 21 GPa at ambient temperature, [4] which means a bonded (unopened) EDA can afford a weight of 211 kg/cm<sup>2</sup>.

It was fully implemented in commercial and specific applications in 1980s. RFID tags can be read at a longer distance and provide more information than barcode. The RFID system is considered as the next generation wireless communication system. [30]

Recent development trends for RFID commercial applications mainly include; size miniaturization, cost reduction, energy saving, and large-scale production, etc. Moreover, RFID technology can be combined with other technologies to expand its application scenarios. EDA is one of them.

Combination of CDM with RFID can find new applications, e.g., (A) An interactive and intelligent packaging solution integrating passive RFID system and EDA was reported by Gao et al. [31] (a) Package opening action is electrically controlled by the RFID system. It brings people convenient and smart lives (b) Reduces consumption of traditional packaging materials and direct or indirect labor costs as well. (c) Interactive and intelligent packaging is an emerging research area in recent years. Being integrated in interactive packaging, Radio Frequency Identification (RFID) technology becomes one of the most proactive development enablers. (B). Pharmaceutical applications. (C) Interactive medication package for pervasive healthcare.

**4.3. Smart dental cement**

Kajimoto noticed the importance of adhesion between

tooth and adhesive for good dental treatment. On the other hand, the adhered brackets and prosthesis had to be removed after the treatment. The removal was carried out by mechanical forces that there remained several risks, i.e., load upon teeth, discomfort to the patient, and damage of the teeth. [32][33] Thus, Kajimoto investigated a detachment system which can debond easily without mechanical force.

The requirements were ‘strong adhesion’ during treatment, and ‘easy detachment’ triggered by some kind of energy, electricity in this case. The product they developed was smart dental cement with decreasing adhesion strength by electricity, obtained by adding ionic liquid to commercial cement.

## 5. Conclusion

Electrically debonding adhesives[EDA], one of the controlled delamination materials[CDM] is reviewed. CDM can be defined as the ability to separate adhesive bonded assemblies without causing damage to the substrates. Its application includes electronics, medical surgery, dentistry, building and general manufacturing where the opportunity to separate assemblies is important. There are several important mechanisms of EDAs; faradaic reaction, phase separation and anode detachment, cathodic debonding, gas emission mechanism, and mechanical stresses. Because the mechanism behind the electrochemical debonding of adhesives is not well understood, this review is made to help the research scientists in the industries.

Finally, new applications of EDA are introduced as new business opportunity. The temporary wafer bonding is one of the novel methods using electrochemically active adhesives. Recent development trends for RFID commercial applications mainly include; size miniaturization, cost reduction, energy saving, and large-scale production, etc. Moreover, RFID technology can be combined with other technologies to expand its application scenarios. EDA is one of them. Thus, combination of CDM with RFID can find new applications, e.g., an interactive and intelligent packaging solution integrating passive RFID system and EDA, which reduces consumption of traditional packaging materials and direct or indirect labor costs as well.

## References

1. B. A. Hutchinson, Y. Liu & Y. Lu, *The Journal of Adhesion*, **93**, 10, (2016).
2. S. Porada et al., *Progress in Materials Science*, **58**, 8, (2013).
3. M. D. Gilbert, US Patent 2008/0196828A1, (2008).
4. J. Welsh, *Structural Dynamics, and Materials Conference*, 7-10, (2003).
5. Y. Lu, J. Broughton, P. Winfield, *International Journal of Adhesion and Adhesives*, **50**, (2014).
6. H. Shiote, C. Sato, M. Ohe, *J Adhes Soc Japan*, **45**, 10, (2009).
7. J. S. Berg, et al., US Patent US9371669B2, (2016).
8. R. McCurdy, Ph D Thesis., *Oxford Brookes University*, (2011).
9. D. Haydon, *Assem Autom*, **22**, 4, (2002).
10. D. E. Packham, *Handbook of Adhesion Second Edition.*, (2005).
11. S. O. Dorst, US Patent US Pat. No. 2,765,267., (1956).
12. EMEC consultants, US Patent No. 5,507,926, (1996).
13. B. WH, Jackson DR., *Transp Res Rec*, (2001).
14. Leijonmarck, S., et al., *International Journal of Adhesion and Adhesives*, **32**, 39, (2012).
15. S. Leijonmarck, Ph D thesis., *Kungliga Tekniska Högskolan, Stockholm*, (2013).
16. WO2010146144A3, JP2012530173A, (2007).
17. WO2005028583A1, (2003).
18. W. J. van Ooij, A. Sabata, D. Loison, T. Jossic, and T. C. Charbonnier, *J. Adhes. Sci. Technol.*, **3**, 1, (1989).
19. Leijonmarck, S., et al., *Journal of the Electrochemical Society*, **158**, 109, (2011).
20. <http://www.eiclabs.com/index.htm> 111 Downey St., Norwood, MA 02062 Tel. (781)769-9450; Fax (781)551-0283.
21. M. D. Gilbert, US Patent: 6620308, (2006).
22. H. Shiote, Y. Sekiguchi, M. Ohe, and C. Sato, *The Journal of Adhesion*, **93**, 10, (2017).
23. M. D. Gilbert, US Patent: 20070269659, (2007).
24. P. Norberg, T. Remonen, X. Wang, M. Sandberg, WO2008150227 A1, (2007).
25. Henkel Ag, WO2017133864A1, EP3199344A1, (2016).
26. The Yokohama Rubber Co., Ltd., EP1914285A1, (2005).
27. H. K. Gatty, S. Schröder, F. Niklaus, N. Roxhed and G. Stemme, *J. Solid State Sci. Technol.*, **3**, 5, (2014).
28. H. Stockman(Air Materiel Command, Cambridge Field Station, Cambridge 39, Mass.).

29. O. K. Ban, A. C. Spielberg, US Patent: US7430398-B2, (2005).
30. J. Gao, Z. Pang, Q. Chen, L. R. Zheng, IEEE RFID, (2010).
31. Kajimoto, Noboru, スマートに剝離可能な新規歯科  
用セメントの開発, (2015).
32. 梶本昇, 宇山恵美, 關根一光, 浜田賢一, 日本齒科  
理工學會近畿中四國地方會夏期セミナー, 大阪,  
(2015).