System Integration for Plastic Electronics Using Room-Temperature Ultrasonic Welding

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Plastic electronics is attracting increasing attention for both high-end applications such as flexible organic light-emitting diode (OLED) displays in mobile phones and low-cost items such as plastic radio frequency identification (RFID) tags for product labeling and tracking. However, there are numerous technological challenges, not least of which is to develop robust and reliable packaging methods. Unfortunately, most of the established packaging technologies used in conventional silicon electronics are not transferable to plastic electronics due to the high process temperatures involved. The use of room-temperature ultrasonic welding for the realization of multilayer plastic electronic circuits is explored, identifying two distinct modes of ultrasonic welding that can form combined electrical and mechanical connections between adjacent low-temperature polymer films with either aluminum or printed silver metallization. Fully functional multilayer wireless charging coils and RFID tags are fabricated to demonstrate the potential of this new system integration approach.

Plastic electronics is a rapidly advancing field, encompassing the design, synthesis, characterization, and modeling of printable and flexible electronic materials and devices. Although conducting polymers were studied as early as the mid-19th century, it was work in the late 1970s,[1] and the subsequent emergence in the mid 1980s of organic light-emitting diodes (OLEDs),[2] organic field-effect transistors (OFETs),[3] and organic photovoltaics (OPVs),[4] that established the era of plastic electronics. During the last three decades, a wide range of organic electroactive materials were developed, bringing the promise of flexible and easily manufactured plastic electronic components and systems.[5,6] In recent years, plastic electronics has made significant inroads into the commercial world, with applications in portable devices, wearables, and Internet of Things (IoT).[7] However there are still obstacles preventing it from becoming a ubiquitous technology.[8]

One of the key challenges is that of system integration and the need for packaging approaches that can yield more complex systems with acceptable long-term reliability.[9] Flexible integrated circuits (ICs) are still primitive compared with their silicon counterparts, and for the foreseeable future, plastic electronic systems for high-end applications will be hybrids in which silicon chips are combined with key plastic electronic subsystems such as displays. The recently announced flexible smart phones are examples of such hybrid plastic electronic (HPE) systems.[9] At the same time, flexible IC technology is advancing, and silicon-free plastic electronic systems are emerging for low-end applications such as those envisioned for IoT.[10,11] The manufacturing of such systems requires the use of low-temperature packaging approaches because flexible ICs and low-temperature polymer substrates cannot survive the high process temperatures associated with traditional solder-based packaging methods. For HPE systems, there is an additional challenge due to the mismatch between the minimum conductor pitch in printed electronics, which is typically several hundred micrometers, and the input/output (I/O) pitch on modern silicon ICs, which may be as low as a few tens of microns. A preferred solution is to use flexible interposers,[12] fabricated by conventional polyimide flex technology, to bridge the gap in conductor pitch. The attachment to the low-temperature polymer substrate then becomes a flex-to-flex process as for flexible ICs.

Much research effort has been devoted to adapting conventional soldering and adhesive packaging for the large-scale manufacturing of flexible electronic systems.[13–17] However, while working processes have been developed for some specific applications, these don’t provide widely applicable system integration solutions for HPE. For example, photonic flash soldering has been applied successfully from the attachment of surface-mount LEDs to flexible printed circuits.[14] However, because of the short timescale of the process, large temperature gradients arise that can potentially damage more complex active devices. Adhesive assembly processes based on both isotropic and anisotropic conductive adhesives (ICAs/ACAs) have also been developed for flexible substrates,[15,16] but there are concerns over reliability (ICA processes) and materials costs (ACA processes.) An alternative adhesive attachment approach based on non-conductive adhesive (NCA) with the potential for improved reliability at lower costs has recently been demonstrated,[17] but this is not a universally applicable joining solution for HPE.

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For example, it cannot solve the important problem of joining aluminum-metalized flexible layers.

In this article, we report a new room-temperature ultrasonic welding method for forming combined mechanical and electrical connections between adjacent polymer layers with patterned metallization. The method is applicable both to the formation of interlayer connections in multilayer circuits fabricated with low-temperature polymers and the attachment of flexible components to such circuits. In this work we have focused on the former application, as shown in Figure 1. The ultrasonic welding operation at the core of the process is shown in Figure 1a–d. Two circuit layers with metal contact pads are aligned and laminated together with an intermediate adhesive layer (Figure 1a,b). The circuit is then clamped between an ultrasonic weld head and an anvil, as shown in the enlarged cross-section (Figure 1c), and a burst of ultrasound is delivered to the weld zone via the sonotrode tip. Under the correct conditions, this leads to the formation of a robust electrical and mechanical connection in the weld zone under the weld stamp (Figure 1c,d). For a complete multilayer circuit, multiple ultrasonic welds will generally be required to provide the necessary interlayer connections. Figure 1e,f shows how this can be achieved for a 4-layer circuit. First, the polymer circuit layers are laser machined with via holes where through-layer connections are required. Next, the circuit layers are aligned with registration marks and laminated using adhesive bonding. Finally, individual ultrasonic welds are used to form interlayer electrical connections, as shown by the red arrows in Figure 1f. For example, jumper A connects layers 2 and 3, jumper B connects layers 1 and 2, and jumper C connects layers 1 and 3.

Ultrasonic welding has been widely used for joining sheet metals and plastics via solid-state welding (metals) or molecular bonding (plastics).\(^{[18,19]}\) However, the ultrasonic welding process reported here differs significantly from these conventional welding methods in two respects. First the weld is formed between metal/plastic bilayers; second the metal thickness is only a few tens of micrometers. Ultrasonic welding experiments were conducted using a custom flip chip bonder adapted from earlier research.\(^{[17]}\) A schematic of the modified bonder is shown in Figure 2a. It comprises an ultrasonic generator (UTHE 20G), a transducer system, a motorized ultrasonic weld head with bespoke sonotrode, and an anvil for holding test samples. Three sonotrode tips (see Figure S1, Supporting Information) with different sizes and weld stamp patterns were fabricated by laser machining of tool steel. The tip shown in Figure S1a, Supporting Information, was used in the welding trials reported here. Two types of circuit layers, both widely used in flexible plastic electronics, were investigated: 40 \(\mu\)m-thick polyethylene terephthalate (PET) with 38 \(\mu\)m-thick aluminum (Al) metallization and 120 \(\mu\)m-thick PET with 8 \(\mu\)m-thick printed silver (Ag) metallization. These circuits were designed with metal tracks.

![Figure 1.](https://www.advancedsciencenews.com) Multilayer plastic electronic circuit fabrication using room-temperature ultrasonic welding: a–d) illustration of 2-layer circuit assembly process; e) 4-layer circuit structure with metal tracks and pads and via holes formed by laser machining; f) 4-layer circuit laminated using adhesive (green layers) and interconnected by spot welding at locations indicated by red arrows.
for four-probe resistance measurement, as shown in Figure S2, Supporting Information. The Al circuits were produced using a standard commercial lithography process. The printed Ag circuits were screen printed in Du Pont-type 5064H conductive ink using an ASM DEK Horizon 03IX printer, with curing at 120 °C for 20 min, as suggested by the ink manufacturer.

According to the basic theory of ultrasonic welding, the strength of a welded joint depends upon the total energy, \( E \), deposited at the welding interface

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E \approx F \times v \times T
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Here, \( F \) is the friction force at the interface, \( v \) is the velocity induced at the interface, and \( T \) is the duration of the ultrasonic burst.\(^{[18]}\) The friction force is proportional to the applied normal load or clamping force, whereas the velocity is proportional to the ultrasonic vibration amplitude. The parameters \( F \) and \( v \) in Equation (1) are therefore varied via the normal load \( F_{\text{load}} \) and the ultrasonic power \( P \) (which sets the amplitude). It was found that ultrasonic power levels of more than 32 W were required to weld the metal/PET circuit layers. The maximum ultrasonic power available was only 40 W, so it was decided to fix the power at 36 W throughout the welding trials. Even at this power, samples processed at the lowest energy levels (\( F_{\text{load}} < 1 \text{ kgf} \) and \( T < 100 \text{ ms} \)) showed no welding and no evidence of damage to the outer surfaces of the PET layers. As the energy was increased through use of larger normal loads and longer bursts, plastic deformation and penetration by the sonotrode tip were observed in the top PET layer, the penetration depth increasing with energy until the metal layers were ruptured. Beyond this point, the PET films started to bond through the gaps in the ruptured metal layers, with the metal around the gaps being crimped and incorporated into the polymer bond, as shown in Figure 2b. The process produces what is effectively a conventional plastic ultrasonic weld while simultaneously providing a crimped electrical connection. Figure 2c shows a cross section through an actual spot weld produced by this process, which we will refer to as Type I welding. Generally, the ultrasonic welding of plastics requires localized melting around the bonding interface, and relatively high deposited energies are needed to achieve this.\(^{[20]}\) In this work it was found that a power level of 36 W with a burst duration of 500–800 ms generated sufficient heating to melt the PET films. A substantial normal load was also needed for deep penetration into the melted PET layer and crimping of the metal foils. The normal load was varied from 2 to 8 kgf in increments of 0.25 kgf. This revealed that the penetration of the PET layers was
insufficient with loads of less than 4 kgf and extended the full depth of the PET layers with loads of more than 6.5 kgf. Based on the above observations the optimized welding conditions for Al circuits were taken to be $F_{\text{load}} = 5 \text{ kgf}$, $P = 36 \text{ W}$, and $T = 600 \text{ ms}$, which generated well-controlled cramped interconnects within the plastic weld without causing excessive penetration. Figure 2d shows the top and bottom views of a typical Type I weld between Al circuits. For the printed Ag circuits, a higher normal load of 7 kgf was required to produce deeper penetration into the 120 μm-thick PET layer.

In addition to Type I welding described earlier, a second form of welding (denoted Type II) was also demonstrated for Al circuits. In this process an ultrasonic weld is formed directly between the metal layers, which remain intact throughout the process. Figure 2e–f shows the concept and a cross section through a Type II welded sample. The Type II process involves two steps. In the first step a relatively high-energy ultrasonic burst is applied that is sufficient to embed the sonotrode tip in the top PET layer but not to rupture the metal layers. A second, lower-energy ultrasound burst is then applied to produce a metal–metal weld. For the Al circuits used in this work, the optimized process conditions for the two welding steps were $F_{\text{load}} = 2.6 \text{ kgf}$, $E = 36 \text{ W}$, $T = 300 \text{ ms}$ and $F_{\text{load}} = 0.26 \text{ kgf}$, $P = 24 \text{ W}$, and $T = 300 \text{ ms}$ respectively. Figure 2f shows the top and bottom views of a Type II weld between Al circuits. Compared with Figure 2d it is shown that the Type II process is less disruptive to the circuit layers.

A Keithley 2000 Multimeter was used to carry out 4 wΩ joint resistance measurements on welded samples. This instrument has an accuracy of 0.1 mΩ and compensates automatically for thermoelectric EMFs when carrying out 4 wΩ measurements. The measured joint resistance of Type I welding was a few mΩ, whereas the joint resistance of Type II welding was lower than 0.1 mΩ and beyond the capacity of the multimeter. The variation of resistance of Type I welding with clamping force was tested while maintaining the ultrasonic power and burst duration at $P = 36 \text{ W}$ and $T = 600 \text{ ms}$. The test results shown in Figure 2b, Supporting Information, are mean joint resistance of five samples with standard deviation versus clamping force at 4, 4.5, 5, 5.5, and 6 kgf. The figure reveals that the optimized welding conditions (5 kgf) produced the lowest average joint resistance of 1.23 mΩ with narrow standard deviation.

To demonstrate the potential of this new welding method we have fabricated multilayer coils. Figure 3a shows a wireless power charging coil comprising three coil layers and a top circuit layer, constructed as shown in Figure 3b. The circuit layers were made from Al-clayed PET film (38 μm-thick Al on 40 μm-thick PET). Each coil circuit comprised nine turns with 750 μm track width and 1.5 mm pitch with two weld pads (Ø2.5 mm) at the open ends. The top circuit layer was designed to interconnect the three coils through the weld pads A to F (Figure 3b, left schematic), and laser cut apertures had been defined in the inner layers to make all the necessary connections possible. The four circuit layers were aligned and bonded together using double-side adhesive tape (3M type 200MP adhesive). The six interlayer connections required to connect the three coils in series were then formed by Type I welding. These included connections between layers 3 & 4, 2 & 4, and 1 & 4, demonstrating that connections could be made between nonadjacent layers. The resulting coil was functional and was used a wireless power pick-up coil for a simple demonstrator based on an LED circuit, as shown in Figure S3, Supporting Information. When connecting across multiple layers, the top layer is stretched down through the laser machined via to the bottom circuit by the weld head, as shown in Figure 3c–e. This stretching generates tensile stress in the top circuit with stress concentrations, as shown by the dotted lines in Figure 3d,e. Excessive tensile stress can lead to delamination after welding; also, welding may cause cracks in the metal layer. The maximum number of layers that could be accommodated with the coil design of Figure 3 was nine. With more than nine layers, delamination of the top layer metallization occurred when trying to form a welded via connection to the bottom layer; this resulted from the excessive distortion caused by pushing the top layer to the bottom of such a deep via hole. The problem could be avoided by having larger via holes or by making top-to-bottom connections in multiple steps via intermediate layers.

As a further proof of concept, both types of ultrasonic welding were used in the fabrication of a simple HPE system in the form of an radio frequency identification (RFID) comprising a silicon chip and a two-layer coil. A commercial RFID chip (EM Microelectronic type EM4423), with dual frequencies in the high frequency (HF, 13.56 MHz) and ultra high frequency (UHF, 860–960 MHz), was used. The chip was 853 × 790 × 152 μm² with six 0.76 μm and 40 μm-high gold bumps arranged at a minimum pitch of 362 μm. Based on the chip specification, each RFID coil had seven turns distributed on a ≈32 mm area at a resolution of 450 μm gap and 900 μm pitch, as shown in Figure 3f–g. The weld pads for the coil assembly were Ø2.5 mm whereas those for attaching the Si chip using ACA were 900 × 900 μm² with a minimum 150 μm gap. Fully functional RFID tags were produced with both types of circuit layers, using the optimized process conditions established in the initial experiments. The overall process is shown in Video S1, Supporting Information (an animation illustrating the entire process flow for the assembly of an RFID tag and a video showing the ultrasonic welding process for Al–PET circuit layers). It was found that Type I welding worked with either Al- or Ag-metalized RFID tags, whereas Type II welding worked only for Al-based RFID tags.

The ultrasonic welding processes demonstrated in this article could provide a route to more complex plastic electronic systems incorporating printed electronic I/O devices (sensors, displays), flexible ICs, conventional silicon ICs, and passive components. A four-step process is envisaged, leading to an encapsulated system that is resistant to moisture ingress and also protected against scuffing or abrasion that might otherwise dislodge or damage the components. The first step is to mount the flexible ICs and other printed or organic electronic devices on a lower circuit layer. These devices may be mounted with their contact pads facing upward for later interconnection by ultrasonic welding or facing down using an alternative approach such as adhesive packaging that can provide electrical connection to the lower circuit layer. The second step is to mount the Si ICs and passives using flexible interposers, with upward-facing contact pads that are amenable to ultrasonic welding. The third step is to attach a prepatterned polymer spaced layer to provide mechanical adhesion and electrical insulation between the lower and upper circuit layers. Laser machining will be used to form via windows, providing clear paths for spot welding and open windows for
sensing. The final step is to attach the upper circuit layer, which provides both encapsulation and additional circuit connections. The top layer will be laminated onto the base circuit using adhesive; then, sequential ultrasonic welding will be used to form interlayer connections. An extension of this approach would be to replace the lower or upper circuit layers by multilayer stacks to provide a higher interconnect density and additional design flexibility (e.g., multilayer coils).

In summary we have successfully demonstrated a new application for ultrasonic welding in the area of plastic electronics packaging. This approach allows the low-temperature bonding of low-cost metal pad materials such as aluminum used in plastic electronics and provides a route to system integration for encapsulated HPE systems. The results of our initial study indicate that ultrasonic welding can form two types of electrical interconnections between PET-sandwiched metal foils. Type I welding leads to a plastic weld combined with the mechanical crimping of the metal contact pads, whereas Type II welding produces a direct metal-to-metal weld. Currently, we are exploring the use of Type I welding to join PET layers with different metallization types, for example, Al and printed Ag. In future works we will study the minimum size of the contact pad that can be reliably welded and look at the influence of metal type and thickness on the ultrasonic welding process; we also intend to investigate...
rolling-type ultrasonic welding as this has the potential to provide a higher throughput than sequential spot welding.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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flexible printed electronics, hybrid plastic electronics, plastic electronics, system integrations, ultrasonic welding

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