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Research

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A Personal Desktop Liquid-Metal Printer as a Pervasive Electronics Manufacturing Tool for Society in the Near Future

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ABSTRACT It has long been a dream in the electronics industry to be able to write out electronics directly, as simply as printing a picture onto paper with an office printer. The first-ever prototype of a liquid-metal printer has been invented and demonstrated by our lab, bringing this goal a key step closer. As part of a continuous endeavor, this work is dedicated to significantly extending such technology to the consumer level by making a very practical desktop liquid-metal printer for society in the near future. Through the industrial design and technical optimization of a series of key technical issues such as working reliability, printing resolution, automatic control, human-machine interface design, software, hardware, and integration between software and hardware, a high-quality personal desktop liquid-metal printer that is ready for mass production in industry was fabricated. Its basic features and important technical mechanisms are explained in this paper, along with demonstrations of several possible consumer end-uses for making functional devices such as light-emitting diode (LED) displays. This liquid-metal printer is an automatic, easy-to-use, and low-cost personal electronics manufacturing tool with many possible applications. This paper discusses important roles that the new machine may play for a group of emerging needs. The prospective future of this cutting-edge technology is outlined, along with a comparative interpretation of several historical printing methods. This desktop liquid-metal printer is expected to become a basic electronics manufacturing tool for a wide variety of emerging practices in the academic realm, in industry, and in education as well as for individual end-users in the near future.

KEYWORDS liquid-metal printer, printed electronics, additive manufacturing, maker, do-it-yourself (DIY) electronics, pervasive technology

1 Introduction

The semiconductor industry continued to follow the famous Moore's Law when Intel introduced the revolutionary Tri-Gate transistors in its 22 nm logic technology in 2011 [1]. As semiconductor processes become more advanced and complicated, interest in finding alternative approaches for the smart manufacturing of transistors is increasing quickly. In 2000, an all-polymer transistor made of an organic semiconductor, conductor, and insulator using inkjet printing was reported [2], triggering an explosion of research into printed electronics. In general, two main aspects of the printed organic transistor arouse people's interest: first, that a conventional mineral-based transistor can be made from organic materials; and second, that printing technology can be used to make electronic devices. Although the printed circuit board (PCB) is well established, it involves the printing of resist materials rather than of electronic materials. In the search for potential low-cost, large-scale, and fast ways to fabricate electronics, outstanding work has been done around the world. Such work can be summed up into two categories: namely, innovations in either printing strategies or in materials. Except for inkjet printing, most fabrication strategies are made possible by micro-contact printing, roll-to-roll printing, and screen printing [3]. To date, a variety of important and functional printing materials [4, 5] have been intensively investigated. Among these, silver nanoparticle ink stands as perhaps the most frequently focused-on conductive ink. At this stage, major challenges in the development of silver nanoparticle ink lie in the high-temperature sintering or intense pulsed-light sintering required for the post-printing processes, its relatively large resistivity, and the potential breaking of printed wires. To overcome the need for a high-temperature sintering process, a type of reactive silver ink has been synthesized that only requires annealing at a mild temperature (90 °C)

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to obtain very high conductivity, as high as the conductivity of the bulk silver [6]. A new silver nanoparticle-based highly conductive ink has been proposed that has a built-in sintering mechanism, avoiding post-sintering completely [7]. However, most of these printing materials still suffer from other undesirable features such as a sophisticated fabrication process and complex printing conditions etc. Thus far, conventional electronics manufacturing strategies are generally environmentally unfriendly; consuming too much time, water, and energy; and requiring overly expensive apparatus. To a large extent, these drawbacks have held electronics manufacturing back from wide-range applications in modern business, and particularly from applications for personal use. It has long been a dream in electronics manufacturing to be able to write out electronics directly, as simply as printing a picture onto paper using an office printer.

In order to provide a reliable and truly direct fabrication of electronics, our lab has proposed a fundamentally different strategy for direct electronics writing (or printing) through the introduction of a new class of conductive inks made of low-melting-point liquid metals or alloys. This method was later named “the Direct Writing of Electronics based on Alloy and Metal Ink,” and abbreviated as DREAM Ink [8]. Through tremendous efforts spent investigating a group of different printing principles over the past few years, the first-ever liquid-metal printer prototype for personal use was invented [3]. Using this machine, we have demonstrated printing out various electronically conductive patterns onto a series of either soft or rigid substrates with high resolution within a scale of 20–80 μm. These patterns range from a single wire to various complex structures such as an integrated circuit, an antenna, sensors, radio-frequency identification (RFID), electronic cards, decorative artwork, classical drawings, and other do-it-yourself (DIY) circuits. The entire process is as short as 15 min. This machine could significantly stimulate a worldwide level of personal practice in electronics manufacturing. Liquid-metal printing is quickly emerging as an excellent way to manufacture electronics at room temperature. As part of a continuous endeavor toward making a pervasive, high-quality, consumer-level printing machine for the coming society, this article presents the close-to-industrial manufacturing process of a liquid-metal printer and interprets its prospective value as an automatic, easy-to-use, and individual-oriented desktop electronics printing machine. The basic features, technical mechanisms, important applications, and potential future of this cutting-edge technology are explained here.

2 Basic features of liquid-metal ink

From its initial use in the thermal management of high-heat flux electronics [9], room-temperature liquid metal is emerging as a very useful material in a wide range of consumer electronics applications. The term “liquid metal” usually refers to modified gallium or a more alloy-based electronic ink, although many different low-melting alloys may possibly be used. The most typical material is $\mathrm{GaIn}_{24.5}$, a eutectic gallium and indium alloy containing a 75.5% mass fraction of gallium and 24.5% indium. $\mathrm{GaIn}_{24.5}$ has a melting point of 15.5 °C [10], which causes it to remain in a liquid state at room temperature (i.e., 20 °C) under normal conditions. Another extremely important quality of liquid-metal inks is that they are safe for human use, unlike mercury, which is well known to be toxic. In this study, we focus our discussion on liquid metals and alloys with melting points around room temperature, namely the $\mathrm{GaIn}_{24.5}$ alloy, which is uniquely important as a printing ink. Its naturally liquid phase and high conductivity ($3.4 \times 10^6\ \Omega^{-1}\mathrm{m}^{-1}$) makes this metal fluid the most promising candidate for an electronics ink that is directly printable at room temperature [3].

It is common knowledge that water forms a droplet on a leaf but sinks into a dusty floor. On the other hand, mercury forms a droplet and rolls across a dusty floor rather than sinking into it. This difference between water and mercury is caused by wettability, which depends on intrinsic surface tension or surface energy. Generally speaking, a leaf has a greater surface tension than a dusty floor, and mercury has a greater surface tension than water. When a liquid drop rests on a flat, solid surface, the contact angle is defined as the angle formed by the intersection of the liquid-solid interface and the liquid-vapor interface (Figure 1).

To measure the wettability of a liquid metal in contact with other solid materials, the contact angles of several normal polymers with $\mathrm{GaIn}_{24.5}$ were measured using POWEREACH JC2000D2, and are depicted in Figure 2. The results indicate that the contact angle of a polymer and the liquid-metal $\mathrm{GaIn}_{24.5}$ alloy decreases approximately as the surface tension of the polymer increases, which can be qualitatively

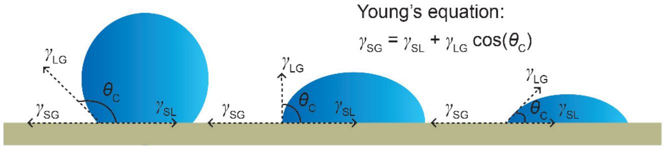

Figure 1. An illustration of Young's equation and contact angles. The surface tensions of the solid and the liquid involved are denoted by γ_{SG} and γ_{LG}, respectively. When the two materials come in contact, γ_{SL} represents the surface tension between them, forming the contact angle θ_C. According to Young's equation, the relation between these four parameters is $\gamma_{SG} = \gamma_{SL} + \gamma_{LG}\cos(\theta_C)$. A contact angle of less than 90° (far right) indicates that wetting of the surface is favorable. Otherwise, the wettability is unfavorable.

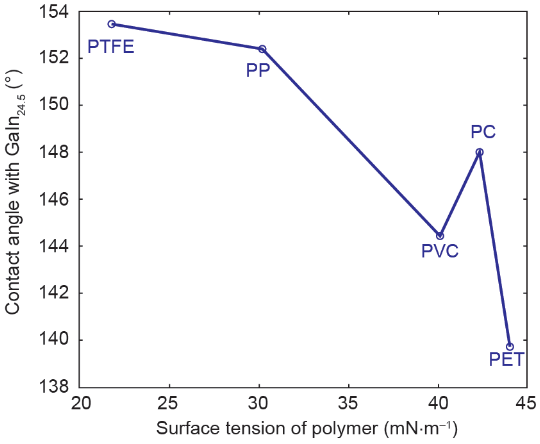

Figure 2. A chart of the contact angles of several polymers with the liquid-metal $\mathrm{GaIn}_{24.5}$ alloy. The surface tension value of each polymer was collected from an ACCU DYNE TEST$^{\mathrm{TM}}$ [12]. Each of these contact angles represents the average value of at least ten measurements, making the results relatively reliable. PTFE: polytetrafluoroethylene; PP: polypropylene; PVC: polyvinyl chloride; PC: polycarbonate; PET: polyethylene terephthalate.