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Review Article

Flexible Electronics: Review and Status

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Abstract: Flexible electronics has undergone different innovations and its applications in different technology is overwhelming. High speed Computation; displays; energy generation; energy storage; flexible substrates; healthcare; human–machine interactivity; lab-on-chip; mobility; sensors; thin-film technology; wireless networks, environmental monitoring and energy conversion are recent development in this field following some optimization processes to enhance their performances and high compatibility.

Keywords: Index Terms: applications, status, compatibility in use, flexible electronics.

1. Introduction

Diodes and transistors are two of the most common active thin-film devices used in a wide range of digital and analog circuits, as well as for detection and energy generation. While they have been successfully used in flexible platforms, their performance and applicability in systems is limited by a number of factors, inevitability requiring, use of exotic device architectures, consisting of highly optimized geometries combined with integration of novel materials. This has often facilitated tailoring of the electronic properties toward particular applications that demonstrate vast improvements in form factor, though typically at significant financial cost, which is unacceptable at the en masse scale.

Flexible electronics has taken its root the past forty years ranging from the development of flexible solar cell arrays made from very thin single-crystal silicon to flexible organic light-emitting diode displays on plastic substrates. The recent development of flexible electronics has been spurred by the continuing evolution of large-area electronics with applications in flat-panel displays, medical image sensors, and electronic paper. Many factors contribute to the allure of flexible electronics; they are typically more rugged, lighter, portable, and less expensive to manufacture compared to their rigid substrate counterparts. The use of flexible electronics enables the availability of robust, lightweight, and low-cost electronics in the near future and a survey of the materials that are used to fabricate these devices on flexible media, the different applications that can be created with a wide variety of materials systems. The range of polymeric to inorganic materials encompasses a wide array of performance benchmarks. It is these properties of device characteristics (both electrical and mechanical) and performance, and the processes involved to make the device that will ultimately determine the suitable applications. Thin-film electronics in its myriad forms has underpinned much of the technological innovation in the fields of displays, sensors, and energy conversion over the past four decades. This technology also forms the basis of flexible electronics. Here we review the current status of flexible electronics and attempt to predict the future promise of these pervading technologies in healthcare, environmental monitoring, displays and human–machine interactivity, energy conversion, management and storage, and communication and wireless networks.

2. Chemical Vapor Deposition (CVD)

Chemical vapor deposition (CVD) is a versatile process suitable for the manufacturing of coatings, powders, fibers, and monolithic components. With CVD, it is possible to produce most metals, and many nonmetallic elements such as carbon and silicon as well as a large number of compounds including carbides, nitrides, oxides, intermetallic, and many others. This technology is now an essential factor in the manufacture of semiconductors and other electronic components, in the coating of tools, bearings, and other wear resistant parts and in many optical, optoelectronic and corrosion applications. It belongs to the class of vapor-transfer processes which is atomistic in nature that is the deposition species are atoms or molecules or a combination of these. Besides CVD, they include various physical-vapor deposition processes (PVD) such as evaporation, sputtering, molecular beam epitaxy, and ion plating. The wide range of CVD products is illustrated by the following recent commercial products (1997):

1. Diffusion barrier layers for advanced semiconductor integrated circuits of titanium nitride deposited by metalloorganic CVD (MOCVD)
2. Diamond-like carbon (DLC) coatings produced by plasma CVD for bushings and textile components with much improved wear resistance.
3. Titanium carbide and titanium nitride coatings for carbide tools that greatly outperform uncoated tools and are taking an increasing share of the market.
4. Iridium, deposited by MOCVD, which has shown remarkable resistance to corrosion in small rocket nozzles at temperatures up to 2000°C.
5. Metallization of semiconductors with copper deposited by MOCVD, replacing aluminum, minimizing electro migration. CVD is now the major process in the production of advanced semiconductor components.
6. Energy saving optical coatings for architectural glass by atmospheric-pressure CVD, produced in situ during the processing of float glass.
7. Pyrolytic boron-nitride crucibles produced by CVD with outstanding chemical inertness, which are used extensively in the electronic industry.
8. CVD boron fibers which are extremely stiff and strong and are used as reinforcement in structural components in aerospace designs.
9. High thermal conductivity CVD-diamond films deposited on heat spreaders or heat slugs to dissipate the heat of high-density integrated circuits.

3. Review Of Materials Considerations For Flexible Electronics

The fundamental properties of thin-film materials, as well as the quality of various device interfaces, give rise to inherent limitations in device performance. For instance, consider the ring oscillator. As one of the most essential building blocks in many systems, it is fundamental to many emerging technologies, such as radio-frequency identification (RFIDs) tagging. A large number of design parameters influence the oscillation frequency of ring oscillators. These include geometric attributes, parasitic capacitance, and the supply voltage. However, these adjustments are often dwarfed by the inherent performance limitations of the transistors. Considering the field-effect mobility as a key performance indicator, one can populate a stage delay Vs mobility map to illustrate the mobility dependency of operating speed of ring oscillators using common semiconductors. The semiconductor–dielectric combination in a circuit is one of the most important considerations for flexible electronics. The achievement of stable high-performance TFTs relies on the optimization of the mobility of carriers and the reduction of traps at the semiconductor–dielectric interface. Thus, the semiconductor and dielectric layers cannot be considered completely independent. The desired fabrication technology also dictates which materials are compatible. It is currently possible to fabricate high-quality TFTs from both inorganic and organic materials. Hydrogenated amorphous silicon (a-Si:H) is the ubiquitous materials system for large-area electronics and is currently used as a semiconductor in liquid-crystal display (LCD) backplanes and X-ray imagers on glass substrates [1, 2]. The integration of high-performance a-Si:H-based TFT devices onto polymeric substrates requires development of high-quality, low-temperature (<200C) processed TFT devices.

The development of such materials has been described in detail in earlier chapters. Particular challenges for flexible substrates are deposition of low mechanical stress layers and the reduction in defect density through optimization of deposition conditions. There are alternative low-temperature methods, such as sputtering. These techniques have generally not achieved the same quality that is possible with PE-CVD. In addition, since the semiconductor and dielectric layers are generally deposited sequentially in the same reactor, the interface formed between these materials can be highly optimized. Alternative inorganic materials to amorphous silicon are currently being explored as semiconductors. Poly-silicon is a well-developed materials system that is currently showing promise in OLED display applications. Recently, a form of silicon that can be jet-printed has been described [3]. This material, however, suffered from the need to be processed in a highly inert atmosphere (<1 ppm O2) and required high-temperature post deposition annealing. Many semiconducting oxide materials, such as ZnO [4] and ternary compounds, In GaO [5], are being widely studied in test devices. These optically transparent materials have the advantage of being deposited at low temperatures while yielding relatively high field-effect mobilities (1–10 cm2/Vs). It is, however, difficult to control their doping level during deposition due to electrically active defects formed during deposition. Printable forms of these materials have also been explored. Nanoparticles of ZnO have been used to form TFTs [6], but can require high temperature (>300C) post deposition anneals for the best performance. TFTs formed with these materials are frequently used with oxide gate dielectric layers, but there are few studies that have explored There are many known semiconducting polymers, but those based on polymers or copolymers of thiophene have generally been the most widely used for TFTs. While most of the characterization of these materials has been performed using thermally grown silicon dioxide gate dielectric layers, they are compatible with a variety of dielectrics including organic polymers, PE-CVD SiO2 and SiNx, and oxides formed from anodized metals [7]. Both p- and n-type organic materials have been demonstrated with the former being more common than the latter [8]. Improvements in n-type materials suggest that organic materials may have an advantage over a-Si:H in applications where complementary logic is required, for example, simple logic circuits.the best candidates for large-area electronic circuits. The choice of the semiconducting system dictates the deposition method. Molecular materials have generally been deposited by vapor methods and have been used in prototype circuits and backplanes. The best pentacene TFTs have reproducible mobilities around 1 cm2 /Vs [9], but in many cases degradation in performance is observed during subsequent processing, such as formation of an encapsulation layer or patterning by photolithography [10]. Small molecules can be made amenable to solution processing by functionalization. Usually, the solution deposition process causes a reduction in the observed field-effect mobility relative to vapor deposition. The typical reason for this difference is the difficulty in controlling film formation as the solvent evaporates. Recently, a number of materials, such as triisopropylsilyl (TIPS)-pentacene, have been designed that form continuous, highly ordered films from solution and now provide high mobility when deposited from solvent [11]. Semiconducting polymers have recently been demonstrated to have mobilities above 0.5 cm^2/Vs, suggesting that they can have similar performance to molecular materials [12].

Most high-performance organic semiconductors form polycrystalline or semicrystalline films. For many materials, it is found that either thermal or solvent vapor annealing can lead to improvements in mobility. The orientation of the crystalline domains relative to the flow of current is considered to be important to achieve the highest field-effect mobility. For example, many semiconducting polymers have lamellar structures where a conjugated backbone is separated by alkyl side chains. Transport is poor along the lamellar stacking direction due to the insulating alkyl side chains and good through the π-stacking direction and along the backbone of the polymer. The interfacial interaction with the gate dielectric must not prevent the semiconducting layer from adopting this orientation during film formation. A variety of low-temperature processable gate dielectrics, including inorganic oxides deposited by sputtering, anodization, or PE-CVD and organic dielectric layers deposited by solution coating, are compatible with organic semiconductors [7].

In flexible electronics, the metals used for the conductors must meet three criteria:

1. they must have a high enough conductivity to not create large parasitic resistance over the area of the circuit,
2. they must inject charge efficiently into the semiconducting layer, and
3. They must not impact deposition of the gate dielectric.

While it is desirable for a single material to meet all requirements, it is not essential. For example, in a-Si:H technology, a doped silicon layer is used for injection and a metal is used for the addressing line and the gate level. In most demonstrations of flexible active-matrix backplanes, the conductors have been deposited from vapor. Direct deposition of molten metal is usually beyond the thermal tolerance of flexible substrates other than stainless steel. The majority of work on conductors has focused on metallic nanoparticles, and organometallic molecular compounds that can be sintered into continuous metallic films [13]. Metallic nanoparticles of coinage metals such as Au or Ag with sizes of<100 nm have reduced melting points relative to bulk materials and can be sintered at relatively low temperatures (<300◦C) [14] or optically with visible lasers [15]. Most nanoparticles are synthesized with an organic surface layer to allow them to be suspended in a solvent without aggregation. While surface layers may be necessary to increase the stability of suspensions of these materials, they are likely to cause injection barriers when used as contacts. For example, contacts formed from silver nanoparticles stabilized with oleic acid appear to show less contact resistance with poly [5,5-bis(3-dodecyl-2-thienyl)-2,2-bithiophene] (PQT)-12 than those stabilized with oleylamine [16]. The origin of this difference could be a modification of the work function of the electrode by the layer or by doping of the semiconducting material near the contact. Semi conducting polymers can form printable conductors when doped and form good contacts to organic semiconductors. Poly (3,4-ethylenedioxythiophene)poly(styrenesulfonate) (PEDOT/PSS) is a widely used printable conductor, but its conductivity is $\sim 10^4$times lower than most metals [17]. Composite films of polyaniline and single-wall carbon nanotubes have better conductivity than PEDOT:PSS (2 S/cm), but still are significantly less conductive than a bulk metal. While organic materials may be used as local contacts, it is unlikely that they can be used for the addressing lines in large-area circuits that require reasonable switching speeds. Printing methods can be broadly classified as noncontact and contact methods. Most high-volume printing, such as packaging, is performed using techniques such as gravure, offset, and flexographic marking where a roller contacts the substrate. The roller may be flat with patterned ink transferred to it from another patterned substrate or the roller itself may have patterned depressions into which the ink is deposited. In electronics, micro contact printing has been demonstrated for patterning of conductors using self-assembled monolayers as resists for chemical etching [18].

The focus here is on noncontact printing, in particular ink-jet printing. Ink-jet printing has been used both to print etch masks for vapor-deposited materials (digital lithography) and for direct deposition of active materials. In digital lithography, the main issues are control of the feature sizes of the printed etch mask and integration of the printing steps into a conventional fabrication process. For printing active materials, attention must be paid to how the material dries or cures into a solid film. In both cases, it is important to understand the fundamental origins of the achievable feature sizes and the ability to control placement of those features.

Flexibility in electronic materials is very attractive for medical and bioengineering. Living organisms are intrinsically flexible and malleable. Thus, flexibility is a necessity for successful integration of electronics in biological systems. Furthermore, in order to carry out daily tasks, flexibility is less likely to hinder over stiffness [19].Recently, some electronics have been integrated into human bodies [19]–[22]. One example is the bionic eye [41]. Here a vision-compromised patient requires an electrically active addressable matrix array, with each unit or pixel recording an image and transmitting this to the patient via the optic nerve [21]. Such technology is not restricted to vision, and is applicable to many other types of sensation.

The bionic ear, shown in Fig. 1, offers an ideal platform for flexible thin-film electronics. In auditory systems, in particular inside the cochlear, the basal membrane of the organ oscillation is a key for listening and fine tuning. With a unique stiffness and geometry, a thin film coupled together with pressure sensing arrays acts as a biomimicking auditory system. At a specific frequency and sound pressure, the basal membrane vibrates at a specific location with predefined amplitude [23]. A microarray pressure sensor can be activated for each specific location, emitting a signal of known pitch and loudness, mimicking the incident sound. Small piezoelectric structures (2–5 m tall) can also be integrated, thereby forming an in-built feedback loop. Normally human ears can fine-tune to cancel noise [and isolate specific sounds of interest. Such feedback mechanisms can oscillate the membrane, so that it vibrates increasingly at a specific frequency, which can amplify the Bsignal[of interests, while canceling otherBnoise[with proximal frequency. In comparison to the current cochlea implant [22], [24], this mechanism allows much wider frequency and sound level to be sensed, much like a real ear. A further application of microarray systems based on such flexible thin-film technology is as a facilitator for artificial noses and tongues, as shown in Fig. 1 Sensory receptors in olfactory (nose) and gustatory (taste) systems have a range of chemical receptors. Many of these receptors sense particular chemical properties, including acidity, salt concentration, and enzyme affinity. The frequency of neurons firing is often sensed in proportion to the magnitude of th eBtaste [orBsmell [23]. Sourness, saltiness, as well as subtypes of sweetness are recognized as pH, alkaline metal, or calcium ions, respectively [25], where these parameters can be extracted by some state-of-the-art electrical impedance analyzer. Molecular compounds, such as sugar or Bumami [precursors can also be converted by enzymes and transducers into measurable electrical signals [26], [27].

Subcutaneous implantation of such thin films, equipped with pH, temperature, pressure, or particular enzyme sensors would be a breakthrough in medicine in terms of real-time patient monitoring and quality of life improvement. If such systems were to be implemented they would be capable of monitoring the elemental content of the patients' blood, thereby extracting valuable data noninvasively. If applied to the wounded on site, critical information on the recovery and survival rate as well as the treatment plan would be instantaneously available, while providing more traditional structural support by being integrated into a bandage, for example. Furthermore, these thin films can also be integrated into bed linen and patient dormitories, and can operate in similar ways to monitor and identify abnormalities in body temperature, as well as sweat elemental analysis. As with the lab-on-a-chip (LOC) applications, these thin films will become a key component of our approach to next-generation healthcare. Heat distribution in the body, sweat content, and frequency or postural pressure on part of the body can all reveal vital information on pathological symptoms or recovering stages.

Also in terms of medical technology, flexible electronics can be installed outside the human body as a diagnostic and monitoring tool. For example, similar heat, humidity, salt, or pressure sensor arrays can be used as a bed sheet and monitor a patient in real time. The body heat distribution, sweat content, and frequency or postural pressure on part of the body can all reveal vital information on pathological symptoms or recovering stages.

Flexible thin films could also play a key role in deciphering the thought processes occurring in the brain. Understanding the underlying neural network and its impact on the physiology and actions of an individual has been the center of many neuroscientists' research, with significant cultural and societal impact. Although different imaging techniques exist today, such as near infrared (NIR) spectroscopy, magnetic resonance imaging, and electroencephalograms, most of these commonly used cognitive tests have limited versatility. Using thin-film multifunctional pixel arrays composed of NIR diodes, detectors, inductors, heat sensors, and electrodes would allow high-resolution multipurpose imaging and stimulation. More importantly, the simultaneously acquired data will give increasing insights on neural signal propagation, processing, and storage mechanisms.

Novel materials are now available that are robust, optically transparent, flexible, and yet electrically active. These include: ZnO-based power generation [29]–[30], thin-film oscillators and wireless power transferring systems [28], and thin-film energy storage and batteries [31], [32]. These examples hint at the possibility of a futuristic deformable film where health monitoring, data processing, data communications, and energy generation and storage can be achieved on a single polymeric platform. However, routes to the control and interaction of the liquid sensing environment with these flexible systems must still be addressed. LOC is one of the most important microsystems for next-generation healthcare, with promising applications in microanalysis, drug development, diagnosis of illness, and disease [33]–[34]. It is envisaged that flexible LOCs may form in situ, plaster-like, wearable health diagnostics and drug delivery. LOCs typically consist of microfluidics, sensors and, in some cases, drive and analysis electronics. Integration of microfluidics and sensors on a single flexible platform can greatly enhance the efficiency of biochemical reactions and the sensitivity of detection, increase the reaction/detection speed, and reduce the potential cross contamination, fabrication time, and cost. However, fabrication techniques of microfluidics and sensors are different, making the integration of the two main components complicated, thereby largely increasing the system cost, particularly on polymer-based substrates.

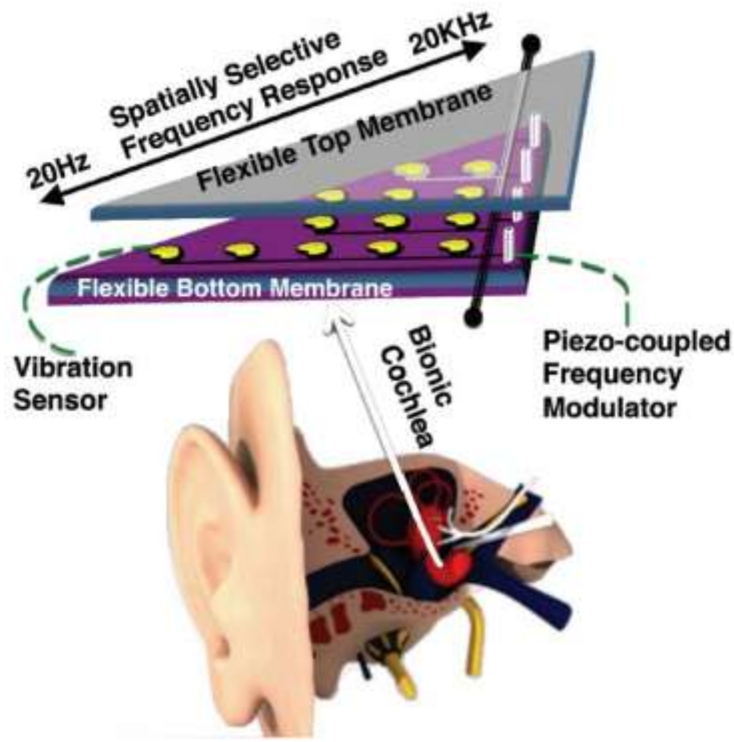

Figure 1. A bionic ear. Ear diagram by Salvatore Vuono (permission obtained). Source {Arokia Nathan et al 2012}

Micro pumps and mixers employing surface acoustic waves (SAWs) as actuation mechanisms are attractive alternatives from an integration perspective [35]. They offer great potential for microfluidic applications, as they are based on low-cost ZnO piezoelectric thin films that can be deposited on commercially available Si and deformable substrates. SAW-based micropumps and micro mixers are simple in structure and fabrication, are inexpensive, and function as active pumping and mixing devices without any moving parts. They have proven reliable and effective [35]. SAW devices have been reported on nano crystalline ZnO thin films deposited on Si substrates using RF sputtering [36]. No direct integration on flexible polymeric substrates has yet to emerge, though this burgeoning field is certain to bloom in time following various technological advancements. When an alternating current (ac) signal at the intrinsic resonant frequency is applied to an interdigited transducer, acoustic waves are generated, through the piezoelectric effect [36], and travel on the surface, as shown in Fig. 2. Coupling of acoustic waves into a liquid induces acoustic streaming and motion of a droplet if in contact with a suitably hydrophobic surface. When the surface energy of the SAW device is reduced, using a self-assembly monolayer perhaps, the acoustic wave can be effectively used to pump droplets. Higher order mode waves, e.g., the Sezawa wave [37], are more effective in streaming and transportation of microdroplets. A SAW device on a ZnO has also been used in [37] to pump and mix liquids remotely, thus avoiding direct contact of the extremely reactive ZnO film with biochemical solutions.

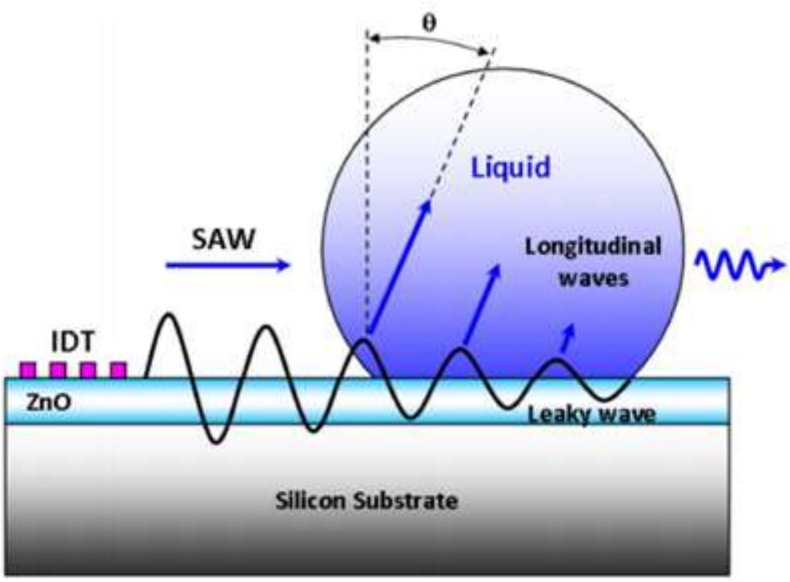

Fig 2.Schematic representation of surface acoustic wave and liquid droplet at Rayleigh angle (θ)

4. Conclusion

Flexible circuits can now be fabricated using both conventional inorganic and organic materials. Optimization of the electrical performance of materials deposited on plastic is still under way. The current level of performance will be adequate for a variety of applications and technologies have been demonstrated to have great utility with commercial instrumentation becoming more widely available, adoption of these methods will probably increase. Some of the significant challenges for adaptation of the materials and designs innovations and technology demonstrated so far are decreasing annealing times, controlling viscosity of solutions without harming electronic properties of the dried films, and development of high-throughput large-scale print heads. Overcoming these challenges will guarantee a drastic reduction burden of manufacturability and flexibility in electronics for their functionality, performance, and cost to permeate into mainstream electronic applications. The unique properties and applications of thin-film flexible electronics are low weight, mechanical flexibility and durability. Simple device integration, along with low-cost and large-area process ability allow them to be utilized in a wide range of applications from space exploration to water purification, and from displays to conformally integrated automotive batteries. Future developments in flexible thin-film technology are likely to enhance the performance of the devices discussed here and more which will lead to more widespread applications.

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