Devising Materials Manufacturing towards Lab-to-Fab Translation of Flexible Electronics

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Flexible electronics have witnessed exciting progress in academia over the past decade, but most of the research outcomes have yet to be translated into products or gain much market share. For mass production and commercialization, industrial adoption of newly developed functional materials and fabrication techniques is a prerequisite. However, due to the disparate features of academic laboratories and industrial plants, translating materials and manufacturing technologies from labs to fabs is notoriously difficult. Therefore, this Progress Report aims to identify key challenges in the materials manufacturing of flexible electronics for its lab-to-fab translation, along the four stages in product manufacturing: design, materials supply, processing, and integration. It also puts forward perspectives on industry-oriented strategies to overcome some of these obstacles. Priorities for action are outlined, including standardization, iteration between basic and applied research, and adoption of smart manufacturing. With concerted efforts from academia and industry, we hope flexible electronics will bring a bigger impact to society as promised.

1. Introduction

Flexible electronics have long been anticipated as the next revolutionary technology for advanced manufacturing and product development, drawing great attention from academia, industry, and governments over the past decade.[1] Industry experts predict the global market for flexible electronics will experience a double-digit growth rate, reaching $250 billion by 2025.[1c] The popularity of flexible electronics arises from its unique advantages in manufacturing and functionality. Potential low-cost, large-area processing and easy production configurability give much cost-effectiveness and flexibility to large-volume manufacturing,[2] while light weight, shape adaptability, and mechanical softness enable functionalities that are not possible by conventional rigid electronics based on complementary metal-oxide semiconductor (CMOS) technology.[3]

The emergence of electronics with mechanically flexible active materials dates back to the 1960s in attempts to make single-crystalline silicon solar cells thinner and lighter for space application.[4] From the 1990s, explorations of organic printed electronics for large-area, low-cost processing generated positive results,[5] but mechanical flexibility of these thin-film electronics was not much appreciated. Over the past 15 years, driven by the needs of shape adaptability and interface softness for electronics used in advanced healthcare,[6] human-machine interface,[7] and Internet of Things (IoT),[1g] flexible electronics witnessed a boom of research progress. A rich library of flexible devices is reported, ranging from integrated circuit components (inverters, ring oscillators, amplifiers, data/power transmission circuits, memories, etc.) to environment-interactive units (energy harvesting and storage devices, sensors, displays, actuators, etc.).[1i, 8] Moreover, mechanical flexibility goes well beyond bendability; devices that are foldable, twistable, crumple-resistance, and stretchable are ubiquitous.[9] Besides, extensive research on soft functional materials propel the advancement of bioelectronics where electronics become imperceptible to vulnerable tissues.[1j, 10]

Despite exciting progress in academia, the adoption of flexible technology in industry is very limited. Currently, the main contributors to flexible electronics market are flexible displays and thin-film photovoltaics, with medical X-ray imagers and radio-frequency identification (RFID) tags holding noticeable market presence.[4] Although there is no exhaustive market research on flexible electronics, estimates of related sectors, such as roll-to-roll flexible devices and printed electronics, report market sizes between 10 to 15 billion USD in 2012 and 2017,[2c, 11] far less than the anticipation. Some pioneering startups offer wearable health monitoring products. For example, BioStamp nPoint®, a multimodal bio-sensing skin patch by MC10, can collect 44 standard metrics in vital signs, activity, posture, sleep, and sEMG (surface electromyography) while conformally attached to the skin. Hexoskin's shirts come with built-in textile ECG (electrocardiography) and respiratory sensors and a precise activity sensor, able to provide clinically validated health data even during active exercise. However, current market size of these medical-grade health monitoring wearables is rather small, partly because the high-end technologies are more accessible to professionals in research and medical fields. The most noticeable disturbance in flexible electronics market recently is perhaps the launch of foldable smartphones by Huawei and Samsung in 2019. Unfortunately, the forbidding price tags and questionable long-term stability stop many consumers from trying out the latest technology. Besides limited product variety and market share, commercial flexible devices only allow some degree of bending, and dynamic deformations during usage is often prohibited. In addition, medical devices, especially implants, that incorporate flexible electronics although frequently reported in academic journals, are far from matured for real-world application.[12]

Clearly, the development of flexible electronics in industry lags largely behind the prosperity in academia, where translational research is urgently needed. The lab-to-fab translation of materials manufacturing is particularly pivotal, since mass production in industrial plants is a prerequisite for commercialization, and novel functional materials and innovative fabrication techniques are the technological pillars for flexible electronics. However, technology transfer from lab to fab is recognized the hardest step in the development path of a tech-intensive industry,[1c] and the multi-disciplinary, cross-industry nature makes the endeavor for flexible electronics more daunting. In this regard, this Progress Report discusses major challenges in the materials manufacturing of flexible electronics to stimulate faster lab-to-fab translation. First, root causes of the contrasting apparent developmental stages in academia and industry are analyzed in terms of device performance and manufacture capability, where the distinction between labs and fabs is highlighted. Next, a brief overview of currently available materials and manufacturing platforms provides an up-to-date technological background. Most of the discussion is then devoted to technical bottlenecks present in design and screening, materials supply, processing and assembling, and system integration. Previous research efforts as well as possible new solutions and research directions are brought up along the way. Finally, the Report concludes by highlighting the importance of a conducive and collaborative research and development ecosystem and raising the awareness of environmental sustainability in materials manufacturing.

2. Unmatched device performance and manufacture capability between labs and fabs

Industrial adoption of flexible electronics is technically hindered by two factors: device performance (assessed by Technology Readiness Level (TRL)) and manufacture capability (assessed by Manufacturing Readiness Level (MRL)) (**Figure 1**). In simple words, devices reported in the literature can hardly serve intended functions in real worlds and are challenging to be manufactured in industrial plants.

Major shortfalls in device performance include durability and level of integration. Demonstrative devices are rarely tested on durability over long-term storage and usage in operational environments. Specifically, mechanical durability (resistance to wear and tear, fatigue), electrical durability (service life, on-off cycles), and environmental durability (stability against humidity, extreme temperatures) should all be sufficiently robust to meet practical requirements. Furthermore, the lack of system-level integration hinders the realization of complete functional devices facing consumers. Although recent years there are some reports on fully integrated flexible systems,[8d, 13] the majority of reported devices still require additional equipment/components to support proper functioning. The abovementioned issues call for action in bridging the gap between TRL4 and TRL6, which entails system validation in laboratory environments to system/subsystem prototype demonstration in operational environments.[14]

On the other hand, industrial manufacturing of flexible electronics is complicated by misaligned manufacture capability in labs and fabs in terms of scale, cost, and quality, due to disparate goals, workflows, and standards. While in-lab fabrication is normally benchtop-scale (device/array area not exceeding m^2 scale) with low throughput (normally a few to tens of devices per batch in a few days), industrial manufacturing must be scaled up to be cost-effective due to the large capital investment in equipment and infrastructure (e.g. average annual fab capacity of Taiwan Semiconductor Manufacturing Company is 1 million 12-inch equivalent wafers in 2018). In parallel, cost reduction is a priority for industrial development, yet often neglected in academic research. Industrial manufacturing also requires precise process control to assure product quality, which usually falls short in benchtop fabrication. This is partly because explorational research largely relies on trial and error and operator experience, yet foundries have detailed protocols and standard operating procedures for every step in production. These differences between academic laboratories and industrial plants underscore the difficulty in bridging MRL5 and MRL7, from prototyping in a production relevant environment to pilot line capability.[14a]

In narrowing the gaps in TRL and MRL, focuses for different types of devices vary due to different application requirements and device construction. **Table 1** gives a more detailed and concrete description of specific gaps in performance and manufacture of flexible electronics used for different applications. In summary, to bring flexible electronics from labs to fabs and eventually to markets, industry-oriented strategies in materials manufacturing must be devised while ensuring durable system performance.

3. A diversifying library of materials and manufacturing technologies

The material candidates for flexible electronics are numerous, stemming from diverse device functions and 'imperfection' of individual materials, i.e. there is no one-size-fit-all material solution. Take flexible thin-film transistor (TFT) as an example; conductors, semiconductors, dielectrics, and substrates are the four major types of materials composing a TFT. As charted in **Figure 2**, potential materials under each category have their distinct characteristics, and no material can concurrently possess all merits for electronic properties, mechanical properties, and processing feasibilities. For instance, crystalline metals and other inorganics used in CMOS electronics are outstanding in electronic properties but they are rigid and brittle, requiring complex design and processing to enable flexibility;[1g] by contrast, emerging organics and nanomaterials are inherently flexible and can be solution processed, yet they suffer from shortages such as low conductivity/carrier mobility and poor stability. Because organics and nanomaterials possess many other favorable features, such as materials design versatility and unique electrochemical properties,[15] there is great interest in solving their processing and performance issues.[11] Additionally, recent emergence of ionotronics incorporating ionically conductive materials,[16] many of which are intrinsically flexible and stretchable (e.g. hydrogels,[17] ionic liquids), opens up more opportunities for flexible devices functioning based on mixed electronic and ionic mechanisms.[18] Overall, the development of flexible electronics is accompanied by a continuously diversifying materials library, incorporating more disordered and organic materials.

To manufacture flexible electronics, CMOS and printing are the major industrial platforms, while many benchtop techniques are dedicatedly developed for new materials in research labs (**Table 2**). Silicon-based CMOS technology is well established over decades to produce state-of-the-art electronics, being dominant in the semiconductor industry. High precision and step complexity are its hallmarks. On the contrary, printing offers a lower quality/resolution approach using simple processes. It is employed in the industrial manufacturing of photovoltaics, TFTs, and displays.[2c] CMOS and printing are tailored for processing different sets of materials. Specifically, clean atmosphere, high vacuum, high temperature, precise alignment, among many other stringent requirements are demanded for producing defect-free, highly crystalline, and sophisticated inorganic structures in CMOS chips. In contrast, printing fully utilizes the solution processability of organics, nanomaterials, and some inorganics, lowering production costs through large-area processing and mild environmental conditions. Apart from industrial manufacturing platforms, benchtop techniques are being actively researched and developed, mainly solution processes manually operated in ambient environment. These techniques are handy options for proof-of-concept fabrication, offering great versatility and customizability. In addition, some novel techniques enable automized processing of emerging materials to deliver superior performance, promising for industrial adoption, such as dry drawing, compatible with roll-to-roll processing, for transparent and conductive carbon nanotube films[19] and one-step laser engraving for patterned graphene on polyimide capable of multiplex sensing.[13c] However, the lab-to-fab translation of novel processes faces challenges in ensuring reproducibility, assessing scalability, machinery innovation, and associated resource sourcing and capital investment. To summarize, CMOS and printing technologies complement each other in cost and device performance, suitable for processing materials with distinct properties, while promising benchtop techniques have to overcome many obstacles before industrial adoption.

4. The thorny path of lab-to-fab translation

Many roadblocks present on the journey of translating proof-of-concept devices to industrially manufactured products, in efforts to narrow the gaps in device performance and manufacture capability. In this section, technological bottlenecks and related research progresses in the materials manufacturing of flexible electronics are discussed in four manufacture stages: design, materials supply, processing, and integration (**Figure 3**), based on which research gaps are identified. Insights on possible solutions are also proposed.

4.1. Efficient screening and design for manufacturability

A successful product design (including material, process, and structure) should deliver a balance between device performance and manufacturing cost. For instance, TFTs, despite being invented in the 1960s, only started to be industrially produced in the 1980s after the discovery that amorphous silicon (material) deposited by plasma-enhanced chemical vapor deposition (process) on glass substrates in an inverted, staggered bi- and tri-layer layout (structure), offers the best cost-performance balance.[20] We have seen the wide variety of design choices in material and process for flexible electronics. In fact, design in structure is also highly diverse due to the many form factors flexible devices can take: 1D fibers, 2D thin films, and even 3D architectures[21]. Moreover, structural design strategies for stretchability, such as wavy or buckled structure, serpentine and fractal designs, and origami and kirigami structures,[8f] further add on to the structural complexity of flexible electronics. With so many parameters to juggle, design challenges for flexible electronics lie in performance quantification, efficient screening, and adequate manufacturability (Figure 3, blue panel).

Performance quantification lays the foundation for initial screening of promising designs, yet the lack of testing standards, especially for characterization under mechanical deformation and for new functionalities, greatly hinders this process for flexible electronics. Currently, researchers in different labs use different methods and parameters to characterize materials properties and device performance. This makes fair comparison across the field impossible, which impedes the research community to reach consensuses on the best-performing candidates. Moreover, as new functionalities are enabled by flexible electronics, unified standards in quantifying and testing these new functions should be specified.[22] There are some published standards for devices related to flexible electronics (e.g. printed membrane switches or printed electronic devices by American Society for Testing and Materials (ASTM), organic transistors and materials by Institute of Electrical and Electronics Engineers (IEEE)), but standards directly addressing flexible electronics are rare. An example is the portfolio of standards for flexible display devices drafted by International Electrotechnical Commission (IEC) starting from 2013. For faster consolidation of guidelines and standards in testing flexible electronics and relevant materials, major stakeholders in the field including academic institutes, professional associations, corporates, and governments should make conscious efforts in collaborating with international standards organizations such as ASTM and ISO (International Organization for Standardization), establishing relevant committees and gathering meetings.

As discussed in previous sections, the material candidates and processing techniques for flexible electronics face different pros and cons in the respect of industrial manufacturing. The same applies for structural design. For example, the buckled structure produced by prestrain-and-release method, a simple process frequently reported in literature, might not be viable for mass production because of the poor control of buckling process over a large area. On the other hand, the serpentine design is readily deployable via conventional CMOS technology (e.g. lithography) but may not be compatible with devices manufactured using non-CMOS techniques. In the design of flexible electronics, the interplay between materials, structures, and processes, as well as resultant device performance and manufacturing cost, needs to be evaluated in a comprehensive and holistic approach. Such vast number of choices with distinct characteristics and close interrelation results in inefficiency in design screening of flexible electronics.

In tackling this challenge, computer-aided design (CAD) turns out helpful. In the first place, a comprehensive database containing materials compositions, processing conditions, and properties should be established, with special attention to mechanical deformation-induced property changes. Building on this, device performance can be partially or fully predictable given structure design and manufacturing parameters, and vice versa, so that efficient decision making on material, structure, and processing can be done.

To implement this CAD process for flexible electronics manufacturing, two imperative elements must be in place. First, thorough fundamental knowledge of materials science, device physics, and processing effects provides scientific guidance to design and manufacture optimization. Second, practical limitations in supply chains, equipment, environment, labor, etc. must be taken into account during the initial product design, which offers valuable engineering considerations for greater manufacturability.[23] To acquire scientific knowledge, extensive experimental studies in academic laboratories are needed, where machine learning can help expedite the process. Machine learning is increasingly recognized as a powerful tool for materials discovery, design, and property prediction.[24] Without knowing the fundamentals governing the behaviors of a type of materials, a computer can self-decipher the structure-property relation and give credible predictions based on limited inputs.[24a] On top of materials screening and discovery, deeper integration of artificial intelligence (AI) will also bring about drastic saving in time, energy, and resources in design and optimization.[25] As for engineering considerations, an intimate collaboration between labs and fabs should be established to provide scientists with a more realistic picture of industrial manufacturing. A greater awareness of ‘design for manufacturability’ will facilitate developing ‘manufacturable science’ and lower the hurdle in translational research.[23]

4.2. Scalable, stable, and processable new materials

Flexible electronics rely heavily on flexible functional materials. Organics and nanomaterials hold great promise in this regard, but their large-scale commercialization is restricted from the early stage of materials supply, including synthesis, storage, transportation, and processability (Figure 3, red panel).

Nanomaterial synthesis has always been a bottleneck for its wide application. Quality, homogeneity, and batch-to-batch consistency of most nanomaterials are not up to standard. Even for one of the most mature nanomaterials, graphene, which is mass-produced worldwide, its quality varies largely from company to company, from batch to batch.[26] While template synthesis[27] and post-processing[2d] are effective to alleviate these issues by additional procedures, microfluidic flow chemistry is promising for well controlled, high-throughput synthesis of nanomaterials in wide ranges of compositions and morphologies in a streamlined manner.[28] On the other hand, conventional batch chemical synthesis generates huge amounts of waste. Thus, devising green synthesis routes such as biosynthesis[29] and cost-effective ways of waste recycling[30] may help make nanomaterial synthesis more economical. From a fundamental point of view, producing materials with dimensions of a few or at most hundreds of atoms with high precision and consistency is inherently challenging. Nevertheless, nature has mastered this skill in the precise replication of DNAs, RNAs, and proteins. Recently, delicate structural control of polymeric nanomaterials was achieved through incorporation of peptides, forming protein-like non-covalent structures.[31] Learning from nature might shed light on energy-efficient, waste-free, and high-quality synthesis of nanomaterials.

The form of materials supply concerns with long-term storage and large-volume transportation, which is also vital for industrial adoption. Although the solution processability of organics and nanomaterials is an advantage for low-cost processing, it can be a drawback for storage and transportation. The use of large volumes of liquid to disperse these materials put on huge pressure on transportation budget, when the production volume goes well beyond lab-scale to fab-scale. Additionally, to prolong shelf-life or improve solubility, additives like surfactants are often added, and surface treatment of functional materials may be carried out, both of which cause performance deterioration on deposition.[2b, 32] Besides, environmental sensitivity (e.g. degradation and structural alteration on exposure to moisture, oxygen, etc.) poses stringent requirements in materials storage.[33] Targeting these challenges, strategies of materials preparation that allow for long-term stability and low-cost storage and transportation, without sacrificing materials performance, are highly demanded. For example, silk fibroin, a promising substrate/dielectric material for flexible electronics,[34] is normally prepared in solution with limited solubility and stability. Recently, researchers successfully prepared the material in powder forms that can be heat molded like traditional thermoplastics into parts of tunable mechanical properties,[35] which is a giant stride towards commercial use of silk fibroin.

Often neglected by academic researchers, the ready processability of raw materials and wide process windows are important for manufacturer acceptance. For instance, silicone as a common substrate for stretchable electronics has very low surface energy, which hinders adhesive integration with other functional materials. General Silicones identified this gap and developed surface-functionalized silicone (Compo-Sil®) that overcomes the poor processability of bare silicone sheets and allows versatile integration for diverse applications. Also, handling of thin polymeric substrates in large area is a tricky yet critical issue, which determines uniformity of materials deposition and resolution of patterning. Transfer printing may be an effective solution through transferring pre-fabricated devices on hard donor substrates to soft acceptor substrates, while engineering efforts to play around with interfacial bonding strength and device structures need to be carefully crafted.[1g, 36] Alternatively, using additional hard carriers below soft substrates can provide robust mechanical support during fabrication, while detachment following device fabrication is one of the complexities.[37] These processability difficulties hamper the large-scale manufacturing of flexible devices on polymer thin films, despite demonstration in centimeter-scale devices.[38] As for process window, it dictates the room for manipulation of processing conditions while maintaining the desired material property; a larger process window allows greater materials compatibility and easier process control. Amorphous oxides, although have high carrier mobility and low-temperature processability,[1f] their narrow process window makes replacement of amorphous silicon in large-area liquid crystal displays a serious challenge.[20]

4.3. Cost-effective and high-quality processing

Existing automated technology platforms (CMOS and printing) provide an industrial playground for process adaptation towards mass production of flexible electronics. Continuous process innovation is required to further improve their cost-effectiveness. Regardless of manufacturing platforms, high interface quality between materials layers is a major challenge for flexible electronics, vital for device performance and stability. In particular, for newly developed functional materials and printing-based processing, device uniformity and stability are the most noticeable issues (Figure 3, green panel).

Mechanically and electronically robust interfaces are much more difficult to achieve in flexible electronics than conventional rigid electronics. While the latter can establish high-quality interfaces through lattice matching, flexible electronics consist of distinct materials of which some are highly disordered and/or with rough surfaces. Furthermore, deformations during usage/processing are a great threat to interfacial stability.[1f, 2b] Smart engineering methods have been proposed to improve interfacial adhesion, such as physical interlocking,[39] chemical modification,[40] and surface activation.[21, 41] Nevertheless, each of these strategies is demonstrated on a single pair of materials and mostly deals with interfaces that do not concern interfacial electronic property (conductor-substrate, substrate-encapsulation). More generalized methodology (e.g. adhesives,[42] large-scale surface functionalization[43]) and more materials combinations (e.g. nano-organic,[44] nano-metallic,[14b] organic-metallic[45]) should be researched on. In addition, more efforts should be devoted to improving electronic interfacial quality under mechanical deformations (e.g. minimizing interfacial traps and scattering, ensuring unaltered work functions).

Due to the contrasting features of CMOS and printing technologies (Table 2), modification of current processes entails different focuses. High cost and low throughput are major barriers to mass production of CMOS-based flexible electronics. This is because additional processing steps are used to enable mechanical flexibility (substrate thinning, patterning, etc.), and delicate handling of ultrathin brittle parts, as well as preservation of structural integrity under harsh processing conditions, compromises manufacturability.[1g] Hence, simplistic device structure design that reduces the number of steps and manufacturing complexity might be a viable approach.[38b]

In contrast to CMOS, performance and reliability are the bottlenecks for printed electronics.[1k] Central issues urgently need to be addressed are uniform and ordered materials assembly at low temperature and maintenance of long-term stability. To solve the first issue, post-processing techniques dealing with energy delivery and tuning of activation energy for crystallization should be devised.[32, 46] Novel printing techniques combined with rational ink selection may produce satisfactory performance even without post-processing.[47] Knowledge in wetting and adhesion, droplet manipulation, and ink viscoelasticity will be needed to craft novel methods for high-resolution, consistent, large-area ink deposition,[43, 48] and non-covalent interactions[49] and phase separation[50] may be explored for precise self-assembly and patterning under mild conditions. Specifically, covalent organic framework, which possesses regular and controllable molecular arrangement when solution-processed at room temperature, can be a source of inspiration.[51] The other issue is long-term stability. Apart from environment-induced degradation, which can be alleviated by proper encapsulation, performance decay of printed devices often originates from intrinsic materials properties such as metastability upon device fabrication and low activation energy for structural rearrangement.[52] For example, when heterogenous organic materials (e.g. donor-acceptor semiconductors) are homogeneously mixed for maximal performance and consistency, immiscible segments gradually phase-separate to reach the thermodynamically stable state during usage. Covalent crosslinking was shown effective in mitigating this type of problems.[53] Improving performance and stability of printed electronics requires fundamental understandings of materials properties and device physics, as well as innovative processing techniques that suppress undesirable physical or chemical alterations.

Against the backdrop of Industry 4.0, the manufacturing sector is facing a ‘smart’ revolution,[54] where flexible electronics can play a part through low-cost production of sensors and development of adaptive soft robotics.[8i, 55] As an emerging technology, it should also take the lead in proactively adopting smart manufacturing, envisioned for higher precision and quality, faster process optimization, and greater customizability. A future factory for flexible electronics might be like this: robotic machinery is engineered with high precision, gentle manipulation, and environmental responsiveness to improve manufacture quality; sensors are embedded in key processing equipment/environment for process monitoring; intelligent quality check systems are installed at the end of each processing step for continuous quality assurance; each produced part and product is marked with digital tags for efficient tracing and inventory record; AI is integrated in production lines for self-directed production optimization; manufacture infrastructures are highly autonomous and programmable for fast production adaption and customization. There have been efforts towards the smart manufacturing of flexible electronics, such as fully printed and 3D printed devices.[47, 56] Together with the fast-evolving computing algorithms and information technology,[57] development in advanced materials manufacturing (e.g. soft material 3D printing[58]) will eventually materialize the vision of smart manufacturing for flexible electronics.

4.4. Robust and integrated hybrid systems

The final presentation of flexible electronics to consumers must be fully functional systems. Due to the wide variety of materials used and repeated mechanical deformations during usage, reliable integration of materials and devices is a tricky task. Hybrid flexible electronics deserves special attention because it combines the high performance of rigid chips and high adaptability of flexible devices, being the most powerful and close-to-maturity flexible electronic systems. While coordination between functional elements requires extensive engineering, major obstacles for hybrid integration come from interconnection and packaging (Figure 3, orange panel).

The challenge of interconnection roots in strain concentration at the soft-hard interface or transition region due to modulus (rigidity) mismatch. It amplifies externally applied strains at mechanically heterogenous locations, which then become a frequent cause of system failure.[59] For example, delamination between rigid metal tracks and soft elastomer substrates remains a reliability bottleneck in some industrially compatible interconnection approaches for multilayer stretchable printed circuit boards.[41c, 60] In solving such problems, several mechanics engineering strategies were proposed to alleviate strain concentration, such as substrate modulus pattering,[61] stiff platform embedment,[62] and fluidic buffering.[63] However, these methods are not readily industrially adoptable or compromise device miniaturization. In comparison, going wireless might be a more viable route for integrated hybrid systems.[64] Using RFID technology, a recent work circumvents the direct interfacing of rigid and soft units by making soft on-skin sensors battery-free and chip-free and attaching stiffer chip-bearing readout circuits on textiles.[8d]

In terms of packaging, primary issues are robust system encapsulation and mechanics engineering. Requirements for encapsulation of flexible electronics can be more stringent than rigid counterparts, when close contact with human tissues occurs (on-skin and implantable systems), liquid materials are enclosed (liquid metals, electrolytes, fluid for mechanical buffering[63]), or harsh environmental conditions are commonplace during operation (building-integrated devices, aerospace applications). From materials perspective, use of both conventional rigid encapsulation materials (e.g. SiN_x, SiO_x, SiC) and flexible polymeric encapsulation materials (e.g. polyimide, Parylene-C, silicones)[12, 65] are necessary to harness the superior passivation properties of the former and mechanical flexibility and durability of the latter. Meanwhile, rational molecular design for new polymers with combined optimal properties should be explored[66] to overcome the current shortfall in barrier properties against moisture and other vapor molecules.[2b, 67] Great challenges emerge when devices of disparate geometries and chemistries within a hybrid system are to be encapsulated monolithically, where traditional planar thin film passivation may not work effectively.[12] Multiple levels of packaging are then required, as in conventional rigid electronics;[68] thoughtful selection of materials and techniques for encapsulating each component, and monolithic system encapsulation compatible to all components, are essential steps. Apart from encapsulation, system-level mechanics design is another important topic in flexible packaging. As encapsulation and substrate make up a significant portion of device volume, their influence on device mechanics is normally larger than functional materials, and they should ideally provide mechanical protection to core functional elements,[1f] through strain redistribution or shock absorption, for instance. Therefore, careful design of system configuration including packaging layers and delicate adjustment of bonding strength between each layer should be in place.[41c, 69] Failure mechanism and cause of system instability should be thoroughly examined following cycling tests. Overall, system integration requires great patience and dexterity in fine tuning the electronic and mechanic coordination between each device unit, as well as multi-level packaging strategies, which deserves more engineering efforts if flexible electronics are to go beyond lab demonstration.

5. Conclusion and outlook

The development of flexible electronics has come to a point where translational research towards industrial adoption critically determines the commercial success of this potentially game-changing technology. However, noticeable gaps between the academia and the industry exist in device performance and manufacture capability. In an effort to narrow and eventually close these gaps, in this Progress Report, we analyzed key challenges in materials manufacturing at every stage of product development and manufacture – design, material, processing, and integration – for lab-to-fab translation. We also proposed some possible solutions and new research directions that will potentially overcome the technical bottlenecks. Based on these proposals, five key thrusts to promote the mass-production of flexible electronics are summarized below and in **Figure 4**.

(1) Standards: There is a pressing need for testing standards to fairly compare candidate materials and devices. With gradual maturation of manufacturing technology and supply chain, standards in materials and equipment specifications, protocols, and workflows will need to be specified and aligned as well. (2) Fundamentals: Scientific knowledge in materials science, device physics, and process parameters is essential for rational design and manufacture problem-solving. This is especially crucial for technology-intensive industries. (3) Engineering: Many of the processing problems require smart engineering approaches. System integration also demands patience in delicate engineering for perfect compatibility and coordination. (4) Artificial intelligence: Use of AI in materials discovery, design screening, and process optimization will greatly improve efficiency and perhaps bring about new scientific breakthroughs. (5) Smart manufacturing: As a potential contributor to Industry 4.0, flexible electronics should lead the trend of smart manufacturing through development of customizable additive techniques, and incorporation of IoT and autonomous robots in large-scale manufacturing.

Besides the abovementioned technological drivers, environmental sustainability deserves more attention in devising manufacturing strategies for flexible electronics. The unprecedented success of CMOS-based electronics comes at a price of compromised natural environment. Current semiconductor processing is highly energy demanding and generates tons of materials scraps. Electronic waste is also an escalating global concern, but recycling has yet to become a common practice. Flexible electronics may be a game changer for the current non-sustainable electronics cycle life. The emerging printing technology has the potential to reduce energy and materials consumption through additive manufacturing at mild conditions. The research on biodegradable electronics and the use of natural materials in flexible devices may provide answers to low-footprint end-of-life disposal.[1h, 70]

The lab-to-fab translation of flexible electronics manufacturing calls for concerted efforts from academia, industry, and governments. Iteration between fabs and labs provides continuous impetus for development and maturation of flexible electronics: practical manufacturing problems encountered in industrial plants are thoroughly investigated in academic laboratories, and fundamental understandings of device physics uncovered in universities aid to further improve manufactured products. Moreover, a right partnership can help break the barriers across fields of expertise and capitalize know-hows within relevant enterprises. Therefore, intimate collaboration between academia and industry as well as cooperation among industry stakeholders should be encouraged from an early stage of technological development, where governments can play a vital supporting role.[1c, 14b]

Technical feasibility being a basis, foreseeable economic value is the driving force for any lab-to-fab translation efforts. Therefore, it becomes crucial to identify the killer applications of flexible electronics, which promise market competitiveness. To this end, market analysis will be essential for researchers to identify competitive edges of their innovations. Innovators also need to tailor their designs according to the needs to target consumers. For example, development of medical devices requires close collaboration with clinicians to identify problems in practice. For building-integrated devices, discussions with construction companies will be necessary to grasp their needs and concerns. After satisfactory TRL and MRL are reached and market competitiveness is justified, challenges still remain ahead of commercialization. Many flexible electronics operate through collecting large volumes of data. Hence regulations in regard to data security and privacy issues must be in place to establish trust between consumers and product/service providers.[71] Cost of regulatory hurdles needs to be taken into consideration, especially for small companies and medical devices.[72] Additionally, social and cultural factors affect the acceptance of novel products and disruptive technologies, calling for adaptive product design and business models. The future of flexible electronics is filled with challenges and opportunities, awaiting to be uncovered by academia, industry, and stakeholders in a wider community.

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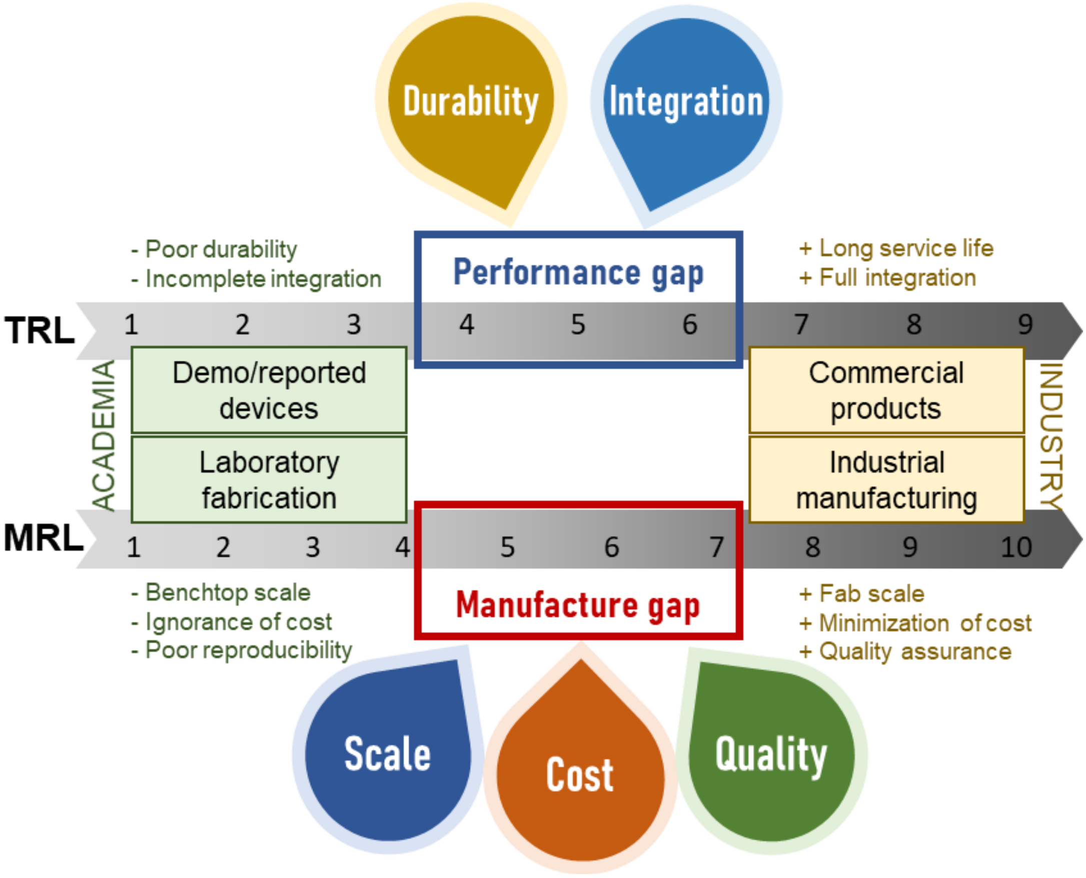

Figure 1. Gaps in device performance (assessed by TRL (Technology Readiness Level)) and manufacture capability (assessed by MRL (Manufacturing Readiness Level)) between flexible electronics in academia and industry. Shortfalls in device performance include durability and integration for fully functional systems in operational environments. Misalignment in manufacture capability lies in production scale, cost, and quality, which stem from disparate goals, workflows and standards in labs and fabs. Detailed differences are listed, where '+' indicates a positive feature for industrial adoption and '-' indicates a negative feature for industrial adoption.

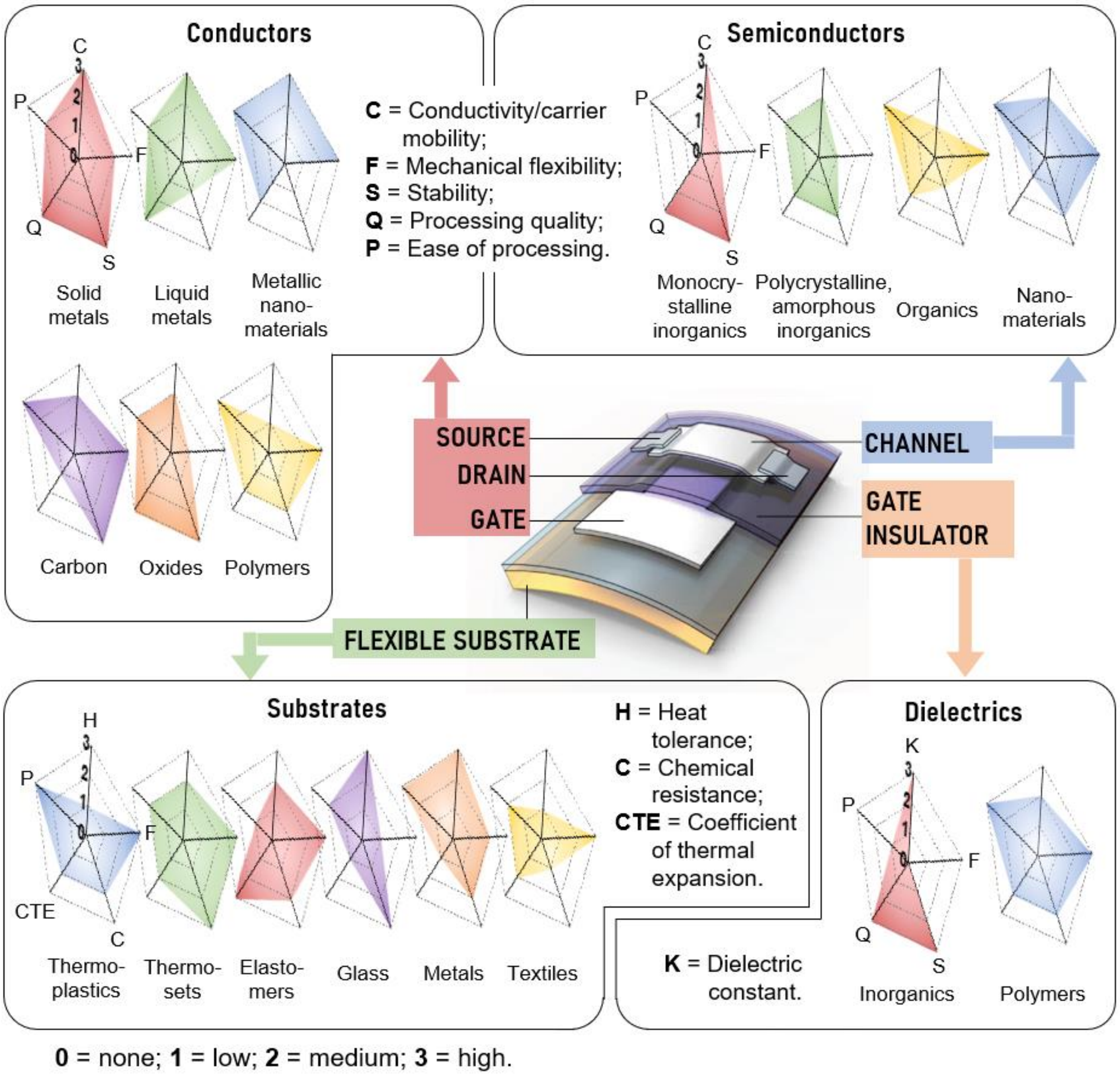

Figure 2. Major categories of materials making up a flexible thin-film transistor (TFT) and qualitative comparisons of candidate materials. A bottom-gate top-contact structure is shown for illustration. Scheme of TFT: Reproduced with permission.[1f] Copyright 2016, WILEY-VCH.

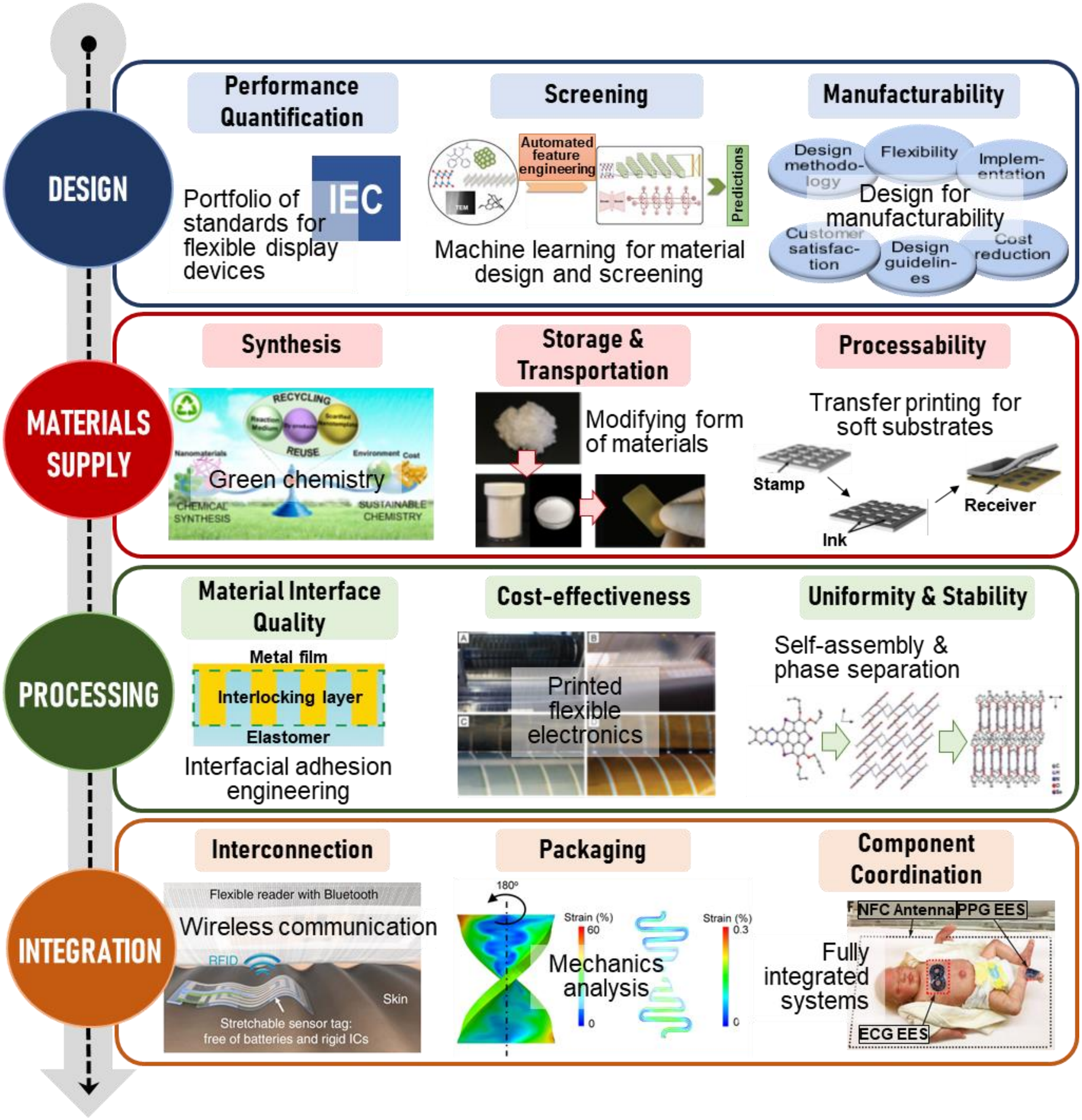

Figure 3. Major challenges and examples of related research outcomes centered on the four key steps in flexible electronics manufacturing: design, materials, processing, and integration. IEC, International Electrotechnical Commission. Scheme of machine learning workflow: Reproduced with permission.[24b] Copyright 2019, WILEY-VCH. Image of green chemistry: Reproduced with permission.[30] Copyright 2019, ACS. Images of silk fibroin: Reproduced with permission.[35] Copyright 2019, The Authors, published by Springer Nature. Scheme of transfer printing: Reproduced with permission.[36] Copyright 2012, WILEY-VCH. Scheme of interfacial engineering: Reproduced with permission.[39b] Copyright 2016, WILEY-VCH. Images of printed electronics: Reproduced with permission.[73] Copyright 2013, WILEY-VCH. Scheme of molecular assembly: Reproduced with permission.[50b] Copyright 2019, WILEY-VCH. Image of a wireless sensor tag: Reproduced with permission.[8d] Copyright 2019, The Authors, published by Springer Nature. Image of mechanic simulation: Reproduced with permission.[13d] Copyright 2020, The Authors, published by Springer Nature. Image of integrated systems on an infant model: Reproduced under the terms of the Creative Commons Attribution license.[13b] Copyright 2019, AAAS.

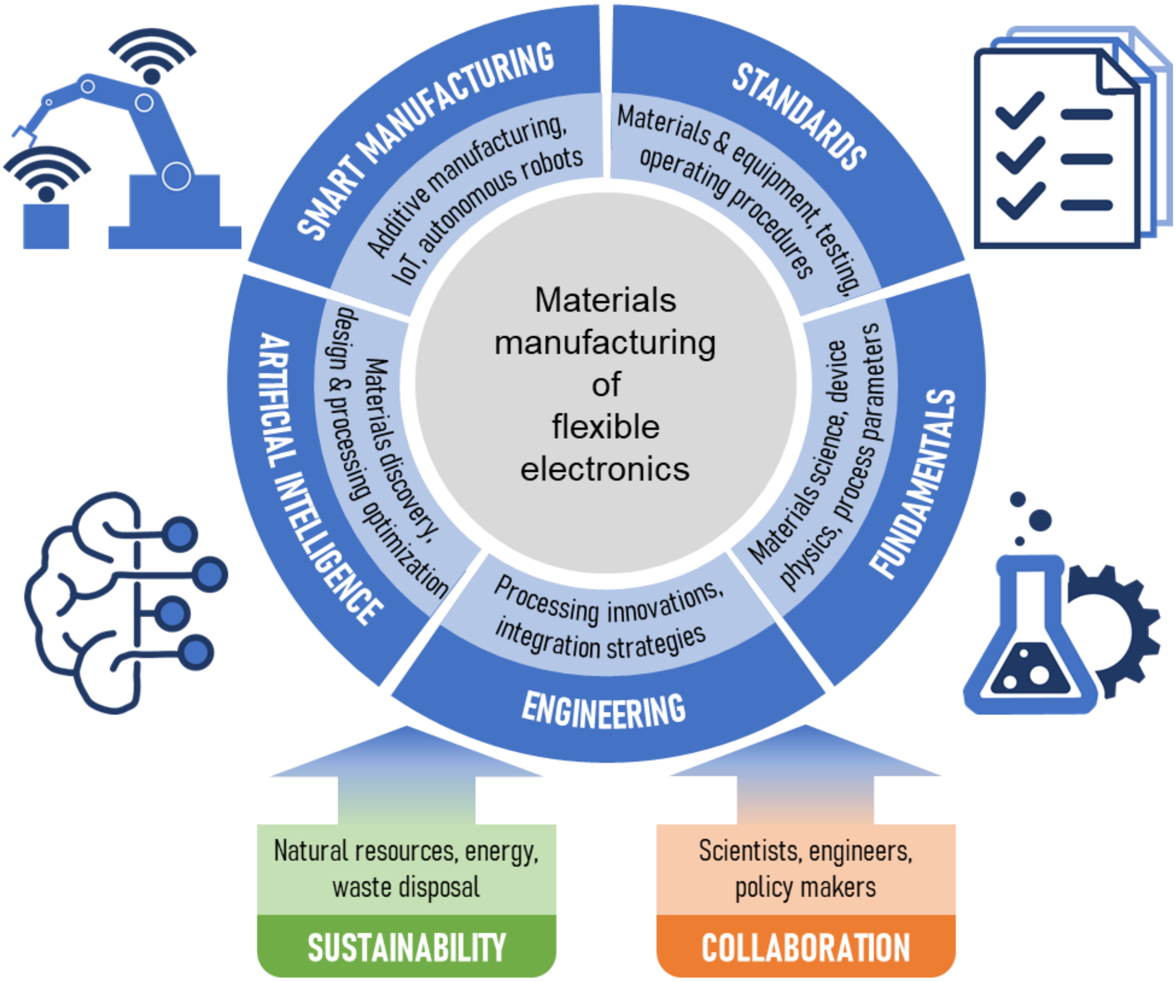

Figure 4. Perspectives on developmental thrusts for materials manufacturing of flexible electronics. Five scientific and technological factors provide continuous impetus, while environmental sustainability and large-scale collaboration are also imperative in guiding socially responsible and effective innovation.

Table 1. Challenges in performance and manufacture of emerging types of flexible electronics, according to potential application scenarios.

Applications	Examples	Challenges in performance and manufacture
Wearable and consumer electronics	Wristbands, headbands,[13a] smart textiles,[1i] smart footwear Foldable smartphones, rollable tablets, e-newspapers	Sensing accuracy and measurement reliability Mechanical durability (wear and tear, folding, stretching) Chemical resistance (sweat, detergent) Aesthetics and wearing comfort (miniaturization, light weight, breathability) Low-cost manufacturing Low energy consumption
Skin-attachable devices[8e, 71b, 74]	Electronic tattoo,[8c, 38, 75] skin patches for health monitoring,[8d, 13b, 63] disease diagnosis and therapy[76]	Sensing accuracy and measurement reliability Softness and stretchability Gentle yet robust skin adhesion even at extreme conditions (swimming, exercising) Wireless communication and signal processing Self-healing Power source[13f]
Robotics and prosthetics[8e, 77]	Sensor-integrated robots,[56a] electronic skin for social robots,[78] electronics in movable robotic parts,[8i] soft robotics, exosuits[79] Prosthetics with sensory feedback,[80] brain-controlled robotic arms,[81] nerve-controlled prosthetics[82]	Sensor sensitivity and spatial resolution Readout electronics[83] and control systems Softness and stretchability, mechanical robustness Multiplexed, cell-specific and long-term stable neural interfaces Light weight and aesthetics Large-area manufacturing at low cost
Implantable devices and tissue engineering	Nerve/brain-interfacing (opto)electronics,[84] cardiac patches,[85] tissue/cell-electronics hybrids[86]	Biocompatibility and immune response In vivo and in vitro stability (including tissue adhesion) Biodegradability[87] or long-term operation (tens of years) Wireless communication Power source
Object-integrated devices for IoT[1g, 2d]	Building-integrated photovoltaics/displays/lightings, aircraft/vehicle-integrated sensors, environmental and agricultural sensing networks, food sensors[88]	Low cost Large area[2a] Stability in harsh environments Long-term operation

Table 2. Comparison of CMOS and printing technologies and benchtop techniques for fabricating flexible electronics.

	CMOS	Printing	Benchtop
Examples of processes	Physical vapor deposition, chemical vapor deposition, epitaxy, annealing, photolithography, e-beam lithography, ion implantation	Inkjet printing, gravure printing, offset printing, flexographic printing, screen printing, aerosol jet printing, transfer printing, 3D printing	Dip coating, spray coating, Langmuir–Blodgett assembly, layer-by-layer assembly, vacuum filtration, electrospinning, wet/dry spinning, electro-/electroless plating, electropolymerization, CO_2 laser engraving[13c, 89]
Processable materials			
Active materials	Inorganics, some organics	Organics, nanomaterials, amorphous metal oxides, liquid metal	Nanomaterials, organics
Substrate materials	Inorganics (e.g. Si, III-V compounds, glass, diamond)	Glass, metals, plastics, elastomers, biopolymers	Paper, fabrics & fibers, plastics, elastomers
Process features			
Atmosphere	Cleanrooms, ultra-high vacuum	Ambient environment or cleanrooms	Ambient environment
Temperature	> 1000 °C	< 500 °C[90]	Room temperature
Scale	100-1000 cm^2 (wafer)	1-100 m^2 (web)	Wide range (mm^2 - m^2)
Single-step throughput	0.001-1 m^2 min^{-1} (batch to batch)	0.1-10 m s^{-1} (roll to roll)[91]	-
Number of steps	100-1000 (level of magnitude)	1-10 (level of magnitude)	Only targeting a few steps in fabricating complete devices
Resolution	> 7 nm	> 1 μm[32]	-
Reliability	High (85-95% manufacture yield)	Medium (30-100% mismatch in TFTs[1k])	Low (poor reproducibility)
Environmental footprint	Materials waste & toxicity, high energy consumption	Little materials waste, low energy consumption	Solvent waste
Process customizability	Low	Medium	High

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Flexible electronics have witnessed tremendous progress in academia over the past decade, but their industrial adoption lags behind the anticipation. To stimulate faster lab-to-fab translation, this Progress Report reviews the current status of flexible electronics, identifies critical challenges in materials manufacturing during lab-to-fab translation, and proposes perspectives on research and development that can expedite the translation process.

Keyword flexible electronics

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Devising Materials Manufacturing towards Lab-to-Fab Translation of Flexible Electronics