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Review:

Optoelectronic platform and technology*

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Abstract: Optoelectronic technology is a new technology formed by the combination of photon technology and electronic technology. Photon technology can cause an industrial revolution that supersedes electronic technology, because it will have a deeper impact on industry and society. We review the development of optoelectronic devices and integration technologies. We compare and analyze the development and characteristics of optoelectronic technology platforms, summarize the key manufacturing technologies, introduce several representative optoelectronic devices including flexible devices, and focus on the key breakthrough technologies that need to be achieved. Through a comprehensive review of the development of optoelectronic technology, China should seize the opportunity for a transformation of the optoelectronic technology industry. By drawing on the experiences with advanced optoelectronic platforms and technologies in foreign countries, we should speed up the accumulation and reserves of Chinese industrial talents, pay attention to the accumulation of basic technology, and establish a national optoelectronic technology platform, to greatly enhance domestic levels in these regards and to achieve independent innovations with these devices.

Key words: Optoelectronic technology; Optoelectronic platform; Process technology; Development and challenges
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1 Introduction

Photoelectron technology, a new technology formed by the combination of photon technology and electronic technology, is a technique to study electron interaction and energy conversion between light and matter. Optoelectronic devices, as the core components of photoelectron technology, consist of a range of functional devices based on electro-photon conversion effect. The development of photoelectron technology has a deep impact on optoelectronics industry and electronic information industry. For example, optical communication and interconnection technology have played a leading role in high-speed broadband networks, high-performance computing, big data, the Internet of Things, and other fields. In recent years, there has been an upsurge in photonics and photon industry. Photon technology will bring an industrial revolution beyond electronic technology, and will have a deeper impact on industry and society than electronic technology.

Optoelectronic devices are generally in the stage of single transistors, and the problems of energy consumption and information system capacity have not been effectively solved. Rapid growth in communication data has put forward high requirements for optoelectronic devices. This means that we must develop optoelectronic devices and integration technologies that are similar to microelectronic integrated circuits. Optoelectronic devices and integration technologies are characterized by wide coverage, rapid development, and frequent adaptations to the nuances of new materials, i.e., new technologies to new devices. Different functional units of optoelectronic devices require different materials and structures which lack standardized designs and manufacturing processes in the way that electronic integrated circuits do; therefore, it has put forward high technological requirements for the development of optoelectronic devices and integrated optical circuits (Gunn, 2006).

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Since the turn of the century, optoelectronic technology has experienced a transition from unit devices to large-scale integration, and the large-scale photonic integrated chips have become one of the most competitive fields in the world. The European Union and other developed countries have elevated the photon integration industry to the level of national strategic planning and development. In the United States, for example, in October 2014, U.S. President Barack Obama announced the establishment of the American Institute for Manufacturing (AIM) Integrated Photonics, which was dedicated to transform the terminal photonics "ecosystem." The birth of AIM Integrated Photonics provides a comprehensive platform for industrial giants, led by International Business Machine (IBM), Intel, and academic institutions, such as Massachusetts Institute of Technology (MIT) and University of California, Santa Barbara (UCSB).

Against the rapid development of overseas backdrop for large-scale photonic integrated chips, China faces enormous challenges, and at the same time, significant opportunities. Domestic research centered mainly at the Institute of Semiconductors, Institute of Microelectronics, Institute of Microsystems, Chinese Academy of Sciences (CAS), Accelink, Huawei, CLP Group, Solectron Suzhou, Tsinghua University, Beijing University, Huazhong University of Science and Technology, Zhejiang University, Shanghai Jiao Tong University, and other institutions and enterprises. These institutes have successively won support from many national major scientific research projects, and they have made great progress in basic theory and device structural designs. However, due to restrictions in technologies and conditions, there is a big gap in theory and engineering aspects compared with foreign countries, which is a strategic and fundamental problem to be solved. China should seize opportunity, lay out talent reserves, and pay attention to the basic process of accumulation by building a national optoelectronic technology platform; thus, we could greatly improve the level of optical devices in our country and our capacity of independent innovations (Yu et al., 2005; Chen et al., 2013; Yang, 2016).

2 Optoelectronic devices

Optoelectronic devices are the key components of the optoelectronic technologies, the frontier research field of modern optoelectronic and microelectronic technologies, and an important part of information technology. Optoelectronic devices have rapidly progressed. New technologies, materials, principles, and products are constantly used. Various new devices are constantly emerging, and device performance is constantly improved. From visible-light to low-light, infrared, ultraviolet, and X-ray detection devices, the detection ranges range from gamma rays to the far infrared and even to the sub-millimeter wave band, and detection elements range from point detection to multi-point detection and two-dimensional (2D) imaging devices. The number of pixels is increasing and the resolution capabilities are also increasing. Given the integration process of micro-optoelectronic technology, the size of optoelectronic devices is becoming smaller. Various new solid-state imaging devices have been successfully developed, replacing the traditional optoelectronic devices in many regards. The requirements of optical information technology are constantly prompting the frequency response of detectors. In addition, many fields require the optoelectronic systems be integrated within flexible, soft, stretchable, and wearable platforms. This is at the heart of the development of energy harvesting, smart textiles, surgical probes and tools, robotics and prostheses, and neuroscience. Both the United States and Europe invest significantly in this highly competitive field, because technological breakthroughs in the field will definitely bring revolutionary changes in many areas (Forrest, 2004).

Incorporated rigid and flat and brittle semiconductor wafers as supporting substrates established forms of inorganic light-emitting diodes to restrict the ways in which the optoelectronic devices can be used. The potential for alternative applications enabled by integration of thin-film devices on flexible sheets of plastic partly motivated the research in organic electronic devices. Many impressive results have been achieved in recent years, several of which are moving toward commercialization. There is growing interest in the use of organic and inorganic micro/nanomaterials in similarly unusual forms on plastic, paper, textiles, rubber, and other flat or curved substrates. Recent advances in mechanics and materials provide routes toward integrated circuits that can offer conventional electrical properties, rigid wafer-based technologies but with the ability to be stretched, compressed, twisted, bent, or deformed into arbitrary shapes. Inorganic and organic electronic materials in microstructured and nanostructured forms, intimately integrated with elastomeric substrates, offer particularly attractive characteristics with realistic pathways to sophisticated realization of devices.

For example, recent advances in mechanics and materials have led to reports of ribbons of thicknesses of 100 nm experiencing peak strains of only 0.0005% upon bending to a radius of curvature of 1 cm. Even when mounted on sheets of plastic with a thickness of 20 mm, strains (about 0.1%) at similar bend radii remain well below the fracture limits (about 1%) (Park et al., 2008). A hemispherical electronic eye camera (Ko et al., 2008) was based on compressible silicon optoelectronics. The authors introduced a mean to produce curvilinear optoelectronics and electronic eye imagers that use well-established electronic materials and planar processing approaches to create optoelectronic systems on flat and two-dimensional surfaces in unusual designs that tolerate compression and stretching to large levels of strain (≥50%). In biological field, successful integration of advanced semiconductor devices with biological systems will accelerate basic scientific discoveries and translations into clinical technologies. In neuroscience generally and optogenetics particularly, inserting light sources, detectors, sensors, and other components into precise locations of the deep brain needs versatile and important capabilities. Salimpoor et al. (2003) introduced an injectable class of cellular-scale optoelectronics that offers such features with examples of unmatched operational modes, including completely wireless and programmed complex behavioral control over freely moving animals.

Kim et al. (2010) reported waterproof AlInGaP optoelectronics on stretchable substrates with applications in biomedicine and robotics, wireless optofluidic systems for programmable in vivo pharmacology and optogenetics, and wireless optoelectronic photometers for monitoring neuronal dynamics in deep brain.

Here, we briefly review several representative optoelectronic devices including flexible optoelectronic devices. Meanwhile, smart fibers and textiles are at the heart of the development of flexible devices. We pay particular attention to fibers with electronic and optoelectronic functions.

2.1 Germanium photodetector integrated in a silicon-on-insulator waveguide

As shown in Fig. 1, the main function of the photo-detector is to convert the optical signal into a current signal. Photoelectric detectors used in fiber-optic communication usually use the optical effect generated by a PN junction to achieve photoelectric conversion. Vivien et al. (2009) experimentally demonstrated a high speed and compact Ge photodetector integrated in a silicon-on-insulator (SOI) rib waveguide. A 42-GHz −3-dB bandwidth was obtained at −4 V with a responsivity as high as 1 A/W at a 1.55-μm wavelength and a 60-mA/cm² low-dark current density.

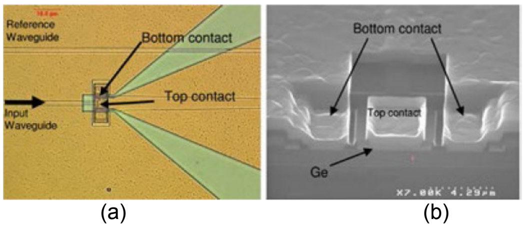

Fig. 1 Optical microscopy top view of the photodetector integrated at the end of the silicon-on-insulator waveguide (a) and the scanning electron microscope cross-section view of the complete pin germanium photodetector (b) (Vivien et al., 2009)

2.2 Gain guided tapered diode laser

Semiconductor lasers have the advantages of small size, light weight, high photoelectric conversion rate, high portability, etc. Single frequency high-brightness laser light sources have become a key component of emerging laser technologies, such as space communication, optical frequency conversion, and optical radar. Ostendorf et al. (2008) grew low modal gain and single quantum well InGaAs/AlGaAs devices emitting at 976 nm by molecular beam epitaxy. They presented investigations of tapered diode lasers based on the InGaAs/AlGaAs material system with different tapered section lengths. For a single emitter device, an optical output power well higher than 15 W has been demonstrated in Fig. 2.

2.3 Solar cell

Fig. 3 illustrates the operational principle of a Sb_2S_3 solar cell and an FTO|TiO_2 nanowire array

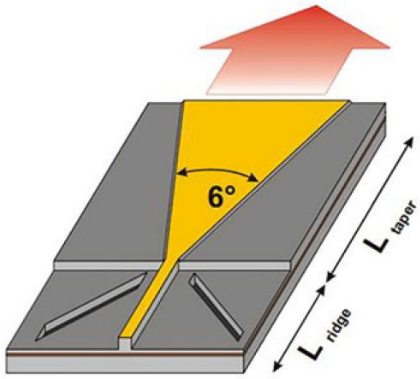

Fig. 2 A gain guided tapered diode laser with a ridge waveguide for mode filtering (Ostendorf et al., 2008)

$|Sb_2S_3|P_3HT|$PEDOT:PSS|Au photovoltaic geometry. Compared with the well developed CIGS, CdTe, and organic/inorganic hybrid perovskite solar cells, the Sb_2S_3-based solar cells have advantages of low cost, non-toxicity, high stability, and excellent photoelectric characteristics. Cardoso et al. (2012) achieved a solid inorganic-organic FTO$|TiO_2$ nanowire array $|Sb_2S_3|P_3HT|$PEDOT:PSS|Au solar cell with a short circuit photocurrent density (J_{sc}) of over 17.01 mA/cm^2, which reached a maximum photoconversion efficiency of 4.65%.

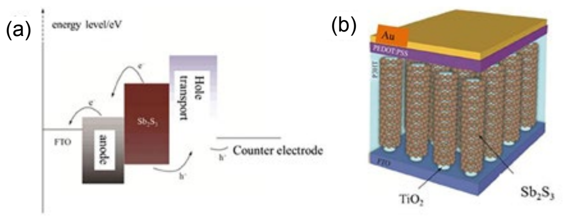

Fig. 3 Operational principle of the Sb_2S_3 solar cell (a) and an FTO$|TiO_2$ nanowire array $|Sb_2S_3|P_3HT|$PEDOT:PSS|Au photovoltaic geometry (b) (Cardoso et al., 2012)

2.4 Flexible devices

Fig. 4a shows images collected by the hemispherical electronic eye camera. Optical setup used collimated green light (argon ion laser) to illuminate a printed pattern on a transparent film. Transmitted light passed through a simple plano-convex lens (diameter: 25.4 mm; focal length: 35 mm) to form an image by the hemispherical camera. Complex pictures (Fig. 4b) can be obtained at a high resolution using this simple scanning approach. Inspection of the images suggests that the stitching errors associated with this process are less than 40 μm, thus validating the accuracy of these models. The nearest-neighbor pixels in the hemispherical camera are separated by about 4°, leading to zero redundancy while generating the tiled picture. These results also demonstrate the high functional pixel yield, which is larger than 99% (Ko et al., 2008).

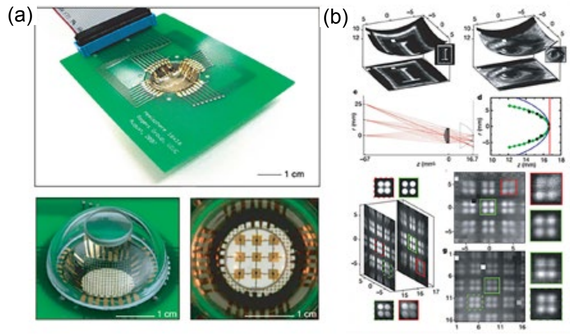

Fig. 4 Photographs collected by a hemispherical electronic eye camera and representative output images (a) and enhanced imaging in hemispherical cameras in comparison with planar cameras (b) (Heung et al., 2008)

In optogenetics, conventional engineering limitations and tethered fiber optic devices restrict opportunities for in vivo use and widespread biological applications. Fig. 5 shows the mechanical compliant and ultrathin multifunctional optoelectronic systems that are mounted on releasable injection needles for deep insertion into soft tissue. These wireless devices incorporate cellular-scale components ranging from independently addressable multicolored microscale and inorganic LEDs (m-ILEDs) to colocated, precision optical, thermal, and electrophysiological sensors and actuators. The combination of m-ILEDs with electronic sensors and actuators yields multifunctional integrated systems that can be configured in single or multilayer formats. The latter option is illustrated in Fig. 5b, in which the sensors and/or actuators include a Pt microelectrode for electrophysiological recording or electrical stimulation, a microscale inorganic photodetector (m-IPD) based on an ultrathin silicon photodiode, a collection of four m-ILEDs connected in parallel, and a precise temperature microsensor or microheater (Kim et al., 2013).

High-efficiency organic LEDs (OLEDs) have gained a lot of attention by low-cost flexible displays and light sources. Wang et al. (2011) reported high-efficiency phosphorescent OLEDs using a thin-film outcoupling enhancement method that does not depend on high-index substrates. An electrode stack consists of a semitransparent gold thin film sandwiched between layers of Ta_2O_5 and MoO_3 (i.e., Ta_2O_5/Au/MoO_3). A high external quantum efficiency (EQE) of about 40% at a very high brightness of 10 000 cd/m^2 was achieved using this new electrode design for a green OLED fabricated on flexible plastic (Fig. 6).

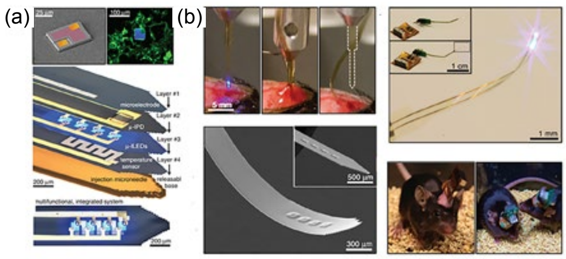

Fig. 5 Injectable and cellular-scale semiconductor devices with multifunctional operation: (a) colorized SEM of a GaN m-ILED; (b) process of injection and release of the microneedle (Kim et al., 2013)

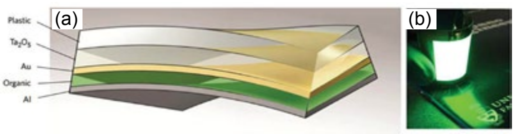

Fig. 6 OLED device structure on low-cost flexible plastic with metal electrodes (a) and photograph of large-area flexible OLED working at high luminance (b) (Wang et al., 2011)

Fig. 7 shows a design of a wireless photometry system. Fig. 7a shows an injectable photometry probe, including a μ-ILED, a related device for photodetection (μ-IPD) placed adjacent to one another on a thin, narrow, and flexible polyimide (PI) substrate with a thickness of 75 μm. A narrow-band absorber photolithographically defined on the top of the μ-IPD serves as an optical filter for block light from μ-ILED to pass photons at the wavelength of the fluorescence. Lithographically patterned metal films serve as electrical interconnects. A coating of polydimethylsiloxane (PDMS) encapsulates the system.

Fig. 7b shows an optical image of a probe terminated in a flexible flat cable (FFC) connector (left) and a colorized scanning electron microscope (SEM) image. Fig. 7c shows the overall multi-layer layout and geometry of the μ-IPD. Figs. 7d and 7e show a layered architecture of transponder and a picture of transponder on a fingertip, respectively. Fig. 7f shows a transponder, an injectable probe (left), and their operation (right). Fig. 7h presents the schematic of the electrical operation. A photovoltaic amplification schemes conditions signals from μ-IPD. μC on the transponder activates the μ-ILED and samples signals from an operational amplifier. An IR LED transmits data to a wireless receiver system via a 38- and 56-kHz modulated carrier frequency and amplitude key shifting. These two carrier frequencies are compatible with a wide range of commercial integrated receivers (Lu et al., 2018).

ILEDs and photodetectors represent important and established technologies for solid-state lighting, digital imaging, and many other applications. Eliminating the mechanical and geometrical design constraints imposed by the supporting semiconductor wafers can enable alternative use in areas such as biomedicine and robotics. Waterproof optical-proximity sensor tapes capable of conformal integration on the curved surfaces of gloves and refractive-index monitors wrapped on tubing for intravenous delivery systems demonstrate the possibilities in robotics. Integration of μ-IPDs with such sensors can yield complete systems. To demonstrate this type of capability and another application, a flexible and short-range sensor could be mounted on machine parts or manipulators, or be used in instrumented surgical gloves. This device exploits co-integration of μ-ILEDs and μ-IPDs in a stretchable format that provides both a source of light and an ability to measure backscatter from a proximal object. Intensity *f* in backscatter can be correlated to the distance from the object. μ-IPDs use reverse-biased GaAs diodes as functional and inefficient detectors of the light emitted from μ-ILEDs. Fig. 8 shows a stretchable optical proximity sensor consisting of an array of μ-ILEDs and μ-IPDs which are mounted on the fingertip of a vinyl glove. This type of system with 4×6 arrays of μ-ILEDs and μ-IPDs is integrated onto the fingertip region of the vinyl glove. Photocurrent measured at μ-IPDs monotonically increases with the decrement of distance from the object, proving the robust operation of this device inside the body or during use in surgical procedures (Kim et al., 2010).

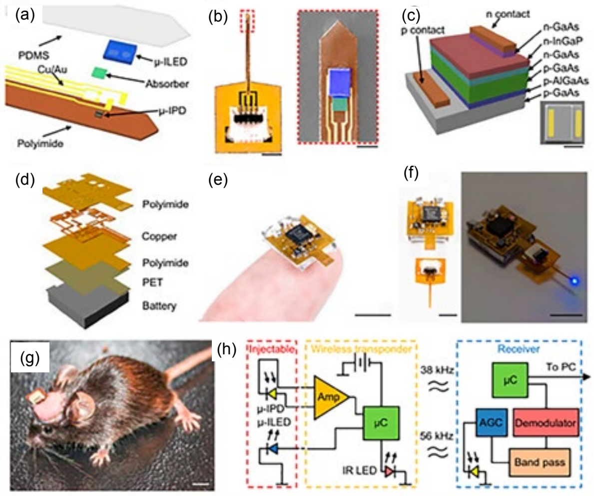

Fig. 7 Miniaturized, ultrathin, lightweight wireless photometry systems for deep-brain Ca^{2+} measurements
(a) Schematic exploded-view illustration of a wireless, injectable, ultrathin photometry probe with a μ-ILED and a μ-IPD at the tip end; (b) magnified colorized SEM image of the tip (orange: PI; yellow: interconnection; blue: μ-ILED; green: μ-IPD with an optical filter); (c) schematic illustration of a GaAs μ-IPD; (d) schematic exploded-view illustration of a transponder; (e) photographic image of the wireless detachable transponder on fingertip (scale bar,1 cm); (f) images of the separated transponder and injectable (left) and the integrated system in operation (right); (g) image of a freely moving mouse with a photometry system; (h) schematic illustration of the electrical operating principles of the system (Lu et al., 2018)

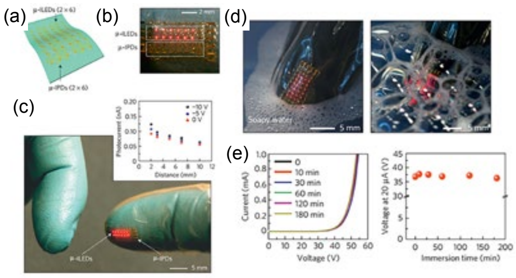

Fig. 8 Stretchable optical proximity sensor consisting of an array of μ-ILEDs and μ-IPDs mounted on the fingertip of a vinyl glove
(a) Schematic illustration of cointegrated 2×6 arrays of μ-ILEDs and μ-IPDs to yield a thin and stretchable optical proximity sensor. (b) Image of the sensor, mounted on the fingertip region of a vinyl glove. (c) Optical images of an array of μ-ILEDs (4×6) with serpentine metal bridges, transfer printed on the fingertip region of a vinyl glove. The inset shows a plot of photocurrent as a function of distance between the sensor and an object (white filter paper) for different reverse biases and different voltages. (d) Left- and right-hand frames corresponding to images before and after immersion into soapy water. (e) Intravenous characteristics of the same μ-ILED array as shown in (c) after operation in saline solution (about 9%) for different immersion times (Kim et al., 2010)

In vivo pharmacology and optogenetics hold tremendous promise for dissection of neural circuits, cellular signaling, and manipulating neurophysiological systems in awake and behaving animals. Existing neural interface technologies, such as the metal cannulas connected with external drug supplies for pharmacological infusions and the tethered fiber optics for optogenetics, are not ideal for minimally invasive and untethered studies on freely behaving animals. Here, we introduce wireless optofluidic neural probes that combine ultrathin and soft microfluidic drug delivery with cellular-scale ILED (m-ILED) arrays (Fig. 9). Fig. 9 shows the wireless optofluidic neural probes that combine ultrathin and soft microfluidic drug delivery with cellular-scale inorganic light-emitting diode (m-ILED). These probes are orders of magnitude smaller than cannulas, and allow wireless and programmed spatiotemporal control of fluid delivery and photostimulation. Fig. 9 shows the overall system with emphasis on the fluid-controlling hardware. Schemes for fluid handling and pumping represent extensions of recently reported drug delivery systems that use rigid, single-channel, and single-reservoir microfluidics, and wired control interfaces. Each of the four channels connects to a separate reservoir, whose base consists of an active layer that initiates pumping via expansion induced by Joule heating in an underlying element (serpentine traces of gold at a thickness of 185 nm). The active layer increases in volume from the thermally induced and irreversible expansion of hollow polymer microspheres that encapsulate hydro-carbon gas. Supporting substrate has low thermal conductivity, minimizing the electrical power needed to reach the temperatures required for this type of thermal actuation. Four reservoirs exist as molded features in a cyclic olefin polymer (COP), chosen for its low water vapor permeability. Thin copper membranes seal the outlets of the reservoirs to prevent evaporation. This design allows delivery of multiple fluids without repeated insertion of a delivery probe (Jeong et al., 2015).

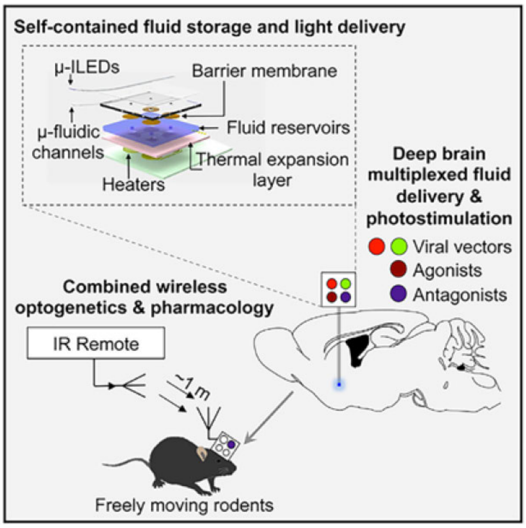

Fig. 9 Wireless optofluidic systems for programmable in vivo pharmacology and optogenetics (Jeong et al., 2015)

2.5 Smart fibers and textiles

Within the broad field of flexible electronics, fiber-based devices rapidly develop as an alternative and versatile platform that can offer functionality in a variety of configurations, due to peculiar geometry, aspect ratio, feature size, and mechanical attribute. Advanced fibers are indeed envisioned to be the next generation optical probes for sensing and minimally invasive surgical tools. They can serve as scaffolds from bioengineered tissues, act as active releasing components in sutures or wound-healing bandages, and form sensing fabrics for soft prostheses or personalized care and the monitoring of physiological parameters. Electronic and optical fibers can form a variety of one-, two-, and three-dimensional sensing networks, such as those integrated in robotics or within structures and composites of health monitoring. Moreover, they can be ideal large-area flexible energy harvesting and storaging systems, using either mechanical or light energy sources. They have the potential to constitute the next generation smart textiles, for which added functionalities will come not from embedded point devices but from the individual textile fibers. An example of these is the creation of the Advanced Functional Fabrics of America (AFFOA), which is a part of the National Network of Manufacturing Innovation (NNMI) Institutes in the United States (Bayindir et al., 2004; Yan et al., 2017).

To realize the advanced fiber-based devices, novel functionalities, optical transport, thermal insulation, and passive mechanical attributes must be developed. Electronic and optoelectronic functionalities are of particular interest, but require the integration of materials with drastically different electronic properties, organized at sub-micrometer scale, and within prescribed architectures. However, functionalization of peculiar fiber geometry, aspect ratio, and materials remains a significant challenge. The state-of-the-art techniques developed for planar and rigid wafer-like substrates are not easily transferred on long, thin, and curved fiber substrates. Despite years of fundamental and applied research, fibers imparted with electronic and optoelectronic functionalities have not yet reached their full potential in terms of performances and applications.

In the past few years, the field of multi-material fibers has taken an important turn toward combining fundamental and applied research. As a result, a series of scientific and technological breakthroughs have been made, reshaping the field and bringing exciting new opportunities. In particular, a deeper understanding of the material science principles behind the viscous flow of materials during and after drawing is essential to reach small feature sizes and complex device architectures. Moreover, the discovery of novel materials compatible with the thermal drawing process and improved control over their microstructure has been a key to integrate more functionalities within devices and improve their performances (Sazio et al., 2006; Sparks et al., 2013). In the following, we will introduce some representative fiber devices, including material, processes, and fabrication methods.

Fig. 10 illustrates the fabrication of multi-material fibers. This approach typically starts with preparing a multi-material macroscopic preform, in which bulk materials are arranged at prescribed positions with a well-defined geometry, as schematically shown in Fig. 10a. Many different methods can be used to make preforms, such as thin-film rolling, consolidation of materials in a vacuum oven or a hot press, the stack-and-draw approach, and additive manufacturing. The resulting preform is then fed into a furnace, where all the constituent materials are soften or melt. An external force applied by a capstan pulls the preform into a fiber (Fig. 10b), the size of which can be tuned by controlling the drawing temperature, the feeding speed of the preform, and the drawing speed. Fig. 10c shows the microstructured optical fibers functionalized by pressure-assisted melt filling and HPCVD techniques (Lee et al., 2011).

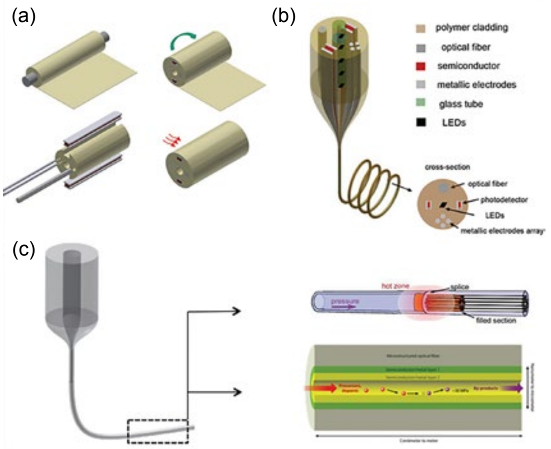

Fig. 10 Fabrication of multi-material fibers: (a) schematic of the fabrication of multi-material preforms; (b) schematic of the thermal drawing of multi-material fibers with several embedded materials and functionalities; (c) microstructured optical fibers functionalized via pressure-assisted melt filling and HPCVD techniques (Yan et al., 2018)

Fig. 11 illustrates the first metal-semiconductor-insulator optoelectronic fiber fabricated by thermal drawing. This fiber comprised an amorphous chalcogenide glass core ($As_{40}Se_{50}Te_{10}Sn_5$) in contact with four metallic microwires and was encapsulated by a transparent polymer cladding, as shown in Fig. 11a. Weaving these fibers into well-positioned optical arrays allowed a follow-up study to extract both the amplitude and phase of an electromagnetic field over large areas for lensless imaging systems. Cascaded thin films could then be fabricated within a single fiber that integrated several photodetecting devices with feature sizes less than 100 nm. Fig. 11b is a case in the point of the advanced hybrid nano-scale configurations that can be fabricated in the fiber form due to multi-material thermal drawing. Moreover, assembling these fibers into 2D grids led to fabrics that could localize an illumination point and perform complex optical tasks, such as a lensless image of an object. Fig. 11d shows a fiber with a Se-based thin film in contact with a SnZn electrode. During drawing, a ZnSe compound was formed, which created a heterojunction with Se within the fiber. The development of optoelectronic fibers within polymer matrices has triggered another research effort to integrate many conventional optoelectronic materials, such as silicon (Si) into the fiber form. The drawing of the semiconducting fibers integrated with Si, Ge, or various compounds precedes this effort, and is originally concerned with extending the transmission bands to other wavelength ranges and integrating stronger nonlinear effects (Yan et al., 2018).

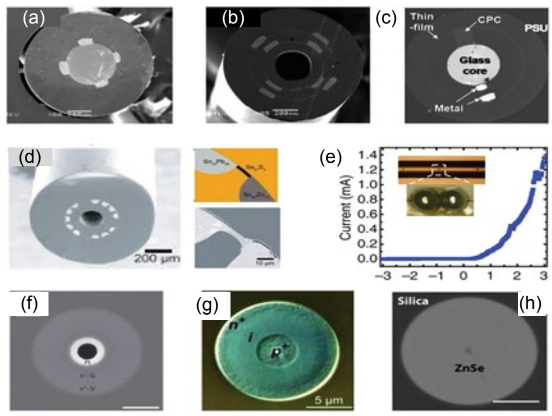

Fig. 11 Metal-semiconductor-insulator optoelectronic fiber fabricated by thermal drawing: (a) the first metal-insulator–miconductor ptoelectronic fiber with a core alcogenide glass connected by four metallic ctrodes; (b) optoelectronic fiber with cascaded semiconducting thin-film configuration; (c) photodetecting fiber that integrates metals, polymer composites, and semiconductors in the core and as a thin film; (d) photodiode fiber in which a fiber draw synthesis reaction forms ZnSe in-between the Se-based layer and the SnZn electrode; (e) a p-n junction fiber formed via in-fiber capillary instability; (f) Pt/n-Si Schottky junctions; (g) a p-i-n junction fiber; (h) a ZnSe optical fiber (Yan et al., 2018)

The field of multi-material fibers is thriving and experiencing increasing research momentum. Policy makers and funding agencies have highlighted functional fibers and textiles as a key advanced manufacturing challenge to be addressed. Industrial interest and funding are rising, and the number of academic groups investing in fiber-drawing capabilities and joining in this field is sharply increasing. This is the result of recent efforts in the field to alleviate materials science and engineering bottlenecks and to develop a deeper fundamental scientific understanding that can serve as a strong foundation for application research. It ensures that the opportunities and limitations are well evaluated, and steers applied research toward the right applications. Indeed, this evolution has occurred alongside novel engineering solutions and application opportunities that have strengthened industry supports.

3 Current trends in the development of optoelectronic technology platforms

Compared with microelectronics technology, the following factors in photoelectron technology, such as the variety of materials and the difficulty in realizing the function of a microstructure by superposition of several simple models in the view of the substrate size of a large number of possible-like microelectronics chips, mean that there is a great difficulty in standardizing photoelectron technology. This raises the threshold of photoelectron chip research and development. From the beginning of this century, to decrease the cost and accelerate the development of optoelectronic chips, many optoelectronic technology platforms have been set up under government grants, and they have played a very positive role in the development of the electronics industry and technology (Zhai, 2009; Li et al., 2016; Zhu et al., 2016).

Photonic integration chip research and industry transformation platform was founded in 2006 based on InP materials, and JePPIX (the European platform for InP-based photonic integrated components and circuits) united all of European InP device integration research and industrializations at the level of colleges and universities, research institutes, and companies to establish a public platform for the general processing technology. Chip process flow sheets are provided mainly by the British Oclaro Company, Germany's Fraunhofer HHI, Dutch SMART Photonics Company, and LioniX Company. HHI and SMART Photonics provide InP substrate multi-project wafer flow service several times a year, and the HHI devices toolbox contains a distributed feedback (DFB) laser and distributed Bragg grating reflection (DBR). Low-loss integrated optical waveguide technology developed by LioniX enhances the coordination among encapsulation, hybrid platform technology based on the InP, and integration technology based on TriPlex.

AIM Photonics, headquartered in the Albany, New York, was based on 12-inch Si material and established in July 2015. It provides complete 65-nm CMOS digital chip technology and silicon photonic integration technology with the most advanced production, assembly, and test capabilities for its participating enterprises, military, and academic institutions. It nurtures high-end photoelectron talent cultivation to improve its competitiveness. Its aim is to build a photoelectron chip foundry, an integrated optoelectronics manufacturing subsystem (including design tools, automatic packaging and testing, and human resources), and a standardized platform for integrated photonics for convenient technology diffusion. It seeks to organize material manufacturers, providers, software providers, users, and researchers to promote cooperations between entities. Its members include famous companies in optoelectronic integration technology, including IBM, Infinera, Intel, Keysight Technologies, Corning, Juniper Networks, Nistica, Samtech，Acacia Communications, Analog Photonics, Aurrion, Axsun Technologies, Chiral Photonics, FiconTEC, and TE Connectivity.

These photoelectron technology platforms have drawn their models from microelectronics integration platform in the hopes of decomposing integrated photonic chips into tiny function modules and establishing the corresponding standard process design kit (PDK) to speed up the development of integrated photonic chips. This technological process is convenient and flexible for custom chips and suitable for large-scale industrial production. The multi-project wafer (MPW) service can greatly decrease the various thresholds and economic pressures of small- and medium-sized enterprises in training photoelectron chip design talent from the outset (Gunn, 2006; Chen et al., 2013).

The Nanofabrication Facility of the UCSB is a standardized development platform with excellent achievements at the college level. It has perfected Si, InP, GaAs, GaN, and SiC process lines, and has achieved many pioneering achievements in active devices and various integrated optical chips. The "Danish Advanced Nanotech Center for Highly Integrated Production" platform, which was established in 1990s and attached to the Technical University of Denmark, provides a full set of open services from deep ultraviolet projection to etching, encapsulation, and testing. In addition, it provides powerful technical supports for the European universities and companies for research into optical waveguide passive devices.

Compared with shared optoelectronic technology platforms in the Europe and United States, domestic photoelectron technology platforms gained momentum relatively late, are centered mainly at scientific research institutes and universities, and do not have an independent commercialized shared photoelectron development platform. Their functions and equipment are relatively simple without a complete system. They lack standardized technology development for key parts, and can realize only small-scale photonic integration. Therefore, it is necessary for China to establish a multi-functional optoelectronic integration technology platform under the umbrella of overall planning, and establish standard process PDK to promote independent research and develop abilities in optoelectronic integration technology (Li et al., 2016).

Besides, in many fields, optoelectronic systems are required to be integrated into flexible, stretchable, and wearable platforms. Flexible electronic technology may bring a revolution in electronic technology, which has attracted worldwide attention and rapidly developed. Science magazines listed the progress in organic electronics technology as one of the top 10 scientific and technological achievements in the world in 2000, which is in line with the major discoveries sketching the human genome and biological cloning technology. American and Japanese scientists won the 2000 Nobel Prize in Chemistry for their pioneering work in conductive polymers.

Flexible electronics can be regarded as a new electronic technology, which fabricates electronic devices by organic/inorganic materials on flexible/ductile plastic or thin metal substrates. With its unique flexibility/ductility and high-efficiency and low-cost manufacturing process, flexible electronics has been applied to information, energy, medical, and other fields, such as flexible electronic displays, indicators, OLEDs, printed RFIDs, thin film solar panels, and electronic surface paste (skin patches). Like traditional IC technology, manufacturing process and equipment are the main driving force for the development of flexible electronic technology. Technical level of flexible electronic manufacturing includes the size of the chip feature and substrate area, and the key is how to manufacture flexible electronic devices with a smaller feature size on larger substrates at a lower cost. Western developed countries have formulated major research plans for flexible electronics, such as the FDCASU program in the United States, the TRADIM program in Japan, and the Poly Apply and SHIFT program in the Seventh Framework Program of the European Union. The Seventh Framework Plan of the European Union alone has invested billions of euros in research and development funds, supporting flexible displays and materials for polymer electronics, basic research on design, manufacture and reliability, batch manufacturing of flexible electronic devices, etc. (Nomura et al., 2004). In the past 10 years, Cornell University, Princeton University, Harvard University, Northwestern University, Cambridge University, and other famous international universities have established flexible electronic technology research institutes, which have carried out a great deal of research on flexible electronic materials, devices, and technology.

Flexible electronic technology has attracted a lot of attention and focus of researchers in China. Much basic research work has been carried out on the preparation of flexible electronic organic materials and the design and application of organic electronic devices, and some progress has been made. The Institute of Applied Chemistry, Changchun Institute of Applied Chemistry, CAS, University of Science and Technology of China, South China University of Technology, Tsinghua University, Xi'an University of Electronic Science and Technology, Tianjin University, Zhejiang University, Wuhan University, Fudan University, Nanjing University of Posts and Telecommunications, Shanghai University, and other institutions have achieved high scores for their work in organic optoelectronics. Sub-materials and devices, LEDs and displays, solar cells, field effect transistors, field emissions, flexible electronic characterization and preparation, flat panel display technology, semiconductor devices, and micro-pattern processing have been studied. In recent years, Huazhong University of Science and Technology has made progress in RFID packaging and roll-to-roll manufacturing, and Xiamem University has made progress in electrospinning.

4 Basic technologies of optoelectronic platforms

4.1 Micronano graphical techniques

Micronano graphical technique (lithography), namely the formation of graphics on the photoresist at the micronano scale, facilitating further transfer of graphics to the corresponding materials, is essential in optoelectronic device manufacturing technology. Lithography technology can realize the photoresist pattern through not only optical exposure but also ion beam and electron beam exposure. Optical exposure has been realized by mask projection with commonly used optical exposure techniques, such as contact exposure, projection exposure, and laser direct writing exposure. Electron beam lithography and ion beam exposure do not need a mask, and directly work through the scanning electron beam and ion beam. These exposure technologies have their own characteristics and application scopes. Contact (near) exposure technology is the earliest and most commonly used photoresist patterning technology. When exposed, pressure or vacuum adsorption is used to make the mask and substrate contact closely to achieve the transfer of graphics. In optoelectronic devices, the most common contact exposure devices are SUSS-MA6 and EVG620. They can achieve a minimum line width of 1 μm and an alignment precision of 1 μm, which can meet the graphical requirements of the vast majority of optoelectronic devices. The equipment has a relatively simple structure, wide adjustability, and low restrictions on the samples; therefore, it has been widely applied in various research and design platforms.

Projection lithography is the main lithography equipment used in semiconductor manufacturing. By adding a narrow lens between mask and exposure wafer, the figure on the mask is projected onto the substrate at a certain proportion (such as 5:1), and the pattern is repeatedly exposed on the entire wafer through repeated steps or scanning. In this exposure method, reduction ratio makes it easier to make the projection mask, and avoids damages to the mask because the mask is not directly in contact with the wafer. The alignment system used in the projection lithography is based mainly on phase grating using grating diffraction alignment marking, and thus the accuracy and efficiency of the image recognition and alignment of the binocular microscope in projection lithography are greatly improved. In addition to the IC industry, projection lithography has been increasingly applied to the research and manufacture of optoelectronic devices, and a considerable number of projection photolithography techniques can be used to realize the photolithography of 2, 4, and 6 inches, or even smaller irregular pieces of photolithography. This approach is directly applied to the development of various non-silicon optoelectronic devices. Fig. 12 shows a modified Nikon i7 projection lithography machine suitable for a 2-inch sample.

Fig. 12 Nikon i7 equipment for a 2-inch sample after modification

The minimum line width is 0.5 μm, the alignment accuracy is 140 nm, and the maximum exposure field is 17.5 mm×17.5 mm.

Electron beam exposure is a very important mean to realize nano-scale graphics, and is a part of device research and development. It is not required to make an expensive photolithography mask, and can be used to design any form of nano graphics directly through software. In the electron beam exposure process, the whole processing area is first divided into fields (Fig. 13), and the fields move through the high-precision worktable to realize graphics splicing. Electron beam is scanned by a deflector in the field.

This process is a vector scanning method; i.e., the electron beam is scanned for only the required exposure area, and the corresponding pattern is filled with the electron beam spot. Because the electron beam spot is very small (about 3 nm), electron beam lithography can obtain nano-scale graphics.

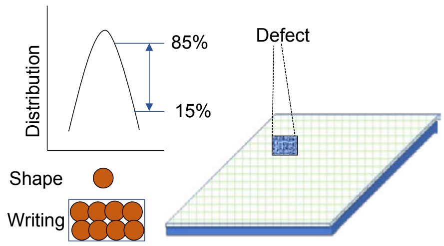

Fig. 13 Principle of electron beam exposure

Lithography, including holographic lithography, ion beam exposure, deep ultraviolet, and X-ray lithography, has its own characteristics and applications. Indeed, lithography can be considered a cornerstone in the development of modern microelectronics and optoelectronic technologies.

4.2 Dry etching technique

Etching technology is an important mean of micro and nano graphic transfer in optoelectronic technology. There are two major categories, dry etching and wet etching. Here, we focus on the dry etching process related to optoelectronic materials and devices.

Several key points in the etching process are: (1) etching rate, selection ratio, and uniformity; (2) orientation of the etching, isotropic etching in the general pure chemical etching process, and various etchings in physical and chemical etching processes; (3) side corrosion, especially a certain side corrosion for non-complete anisotropic etching, which should be avoided or used according to specific conditions in the device.

In a narrow sense, dry etching is especially used in physical and chemical processes produced by plasma discharge to process the surface of the materials. Plasma is an ionized gaseous material composed of positive and negative ions and electrons and neutral particles produced by atomic ionization. Etching related plasma generally has the following characteristics: (1) difference between the three forms of the matter is generally thought to be the fourth state, sometimes called a chemical "soup;" (2) it is considered dynamic as it is constantly accompanied by the generation and disappearance of particles; (3) electrons have very small mass, so there is a high-speed motion; (4) mass is large, while the velocity is very slow; (5) neutral particles are similar to ions, and the velocity is very slow.

In dry etching, plasma is usually produced by the plate capacitance structure, and one of the most important concepts is self-bias. Here, we discuss the generation of self-bias and its important role in etching. As shown in Fig. 14, the anode and cavity of the general etching machine are grounded, and the cathode is connected to the radio frequency (RF) source. As mentioned earlier, electrons are much faster than ions, so electrons can more easily reach the internal insulators. The cavity is grounded (potential 0), so the plasma is slightly positive; that is to say, the plasma has a higher positive potential.

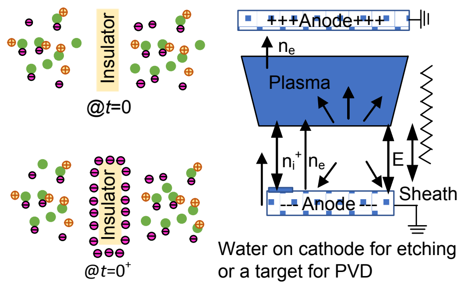

Fig. 14 Potential and distribution of each ion in an etching machine

In Fig. 15, because the plasma has a high potential and the electrons move easily to the cavity, there must be a certain bias, which is a self-bias voltage to push it away from the cavity to maintain the dynamic balance. In Fig. 14, a high electric field is formed near the cathode. Electrons are accelerated and bombarded to produce more electrons and ions. The region does not emit light (sheath region). Outside the sheath zone, a large amount of plasma is gathered, and there is glow discharge that forms an equipotential region. There is a high electric field near the anode region, which is much smaller than that near the cathode region.

Based on the concept of self-bias, we can further discuss the behavior of various particles in the cavity and their respective roles in the etching process from a qualitative perspective: (1) Positive ions enter the

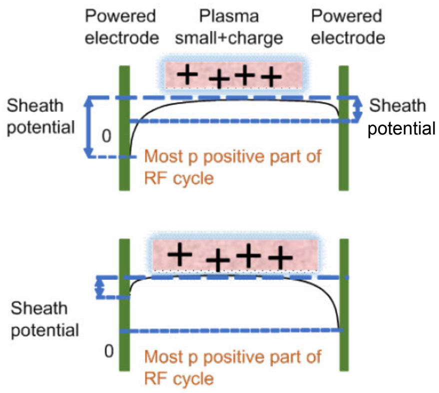

Fig. 15 Formation of a self-bias

sheath region from the plasma region (glow area), bombard the sample, and play a major role in the etching process and its response to the DC electric field without response to the RF electric field. (2) Negative ions are pushed away from the cathode into the glow area. (3) Electrons are pushed away from the cathode into the glow area and oscillate. There is more plasma and an electron response to the RF electric field. (4) The movement of neutral particles on the surface of the sample at the cathode will react with the sample to produce etching effect.

Commonly used plasma etching equipment usually assumes several configurations (Fig. 16). Cavity is connected to the anode in the left, RF source is connected with the cathode, the sample is placed on the cathode, and the most typical reaction ion etching (RIE) occurs. The medium is called "plasma etching" (PE), is contrary to the RIE connection, and is pure on the plasma. Active groups are chemically etched to the samples and basis of the RIE, and the RF source and matching circuit are configured to produce the plasma; thus, the plasma concentration and etching rate are high.

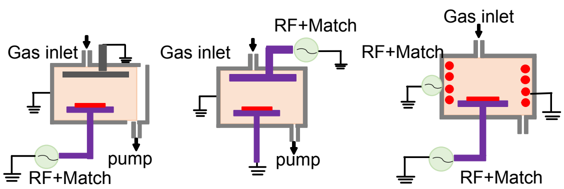

Fig. 16 Common plasma etching equipment

There are several processes in plasma etching, which play a very important role. Here, we will briefly discuss them.

1. Ion sputtering (Fig. 17)

Positive ions are bombarded by the electric field to bombard the sample surface, and the sputtering products are evacuated by the vacuum system. This is a physical process. With a low selection ratio, the etching rate tends to become larger at a smaller pressure. Because the sputtering product may not be gaseous, it may produce an associated anti-sputtering effect.

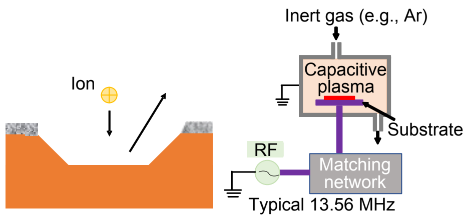

Fig. 17 Ion sputtering etching

2. Chemical etching (Fig. 18)

Active groups react with the sample, and the gaseous reactants are removed to produce etching. The process is a chemical process with a high selectivity ratio, generally dominated by neutral groups. PE etching is a pure chemical etching process.

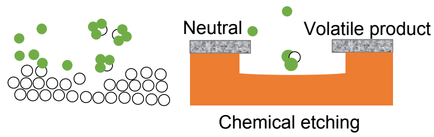

Fig. 18 Chemical etching

3. Ion enhanced etching (Fig. 19)

In the standard RIE etching, the surface of the ion bombardment sample produces a physical sputtering etching, while the chemical active group will react with the loose sample atoms and produce further etching. The process has a high selectivity ratio, etching rate, and good anisotropy.

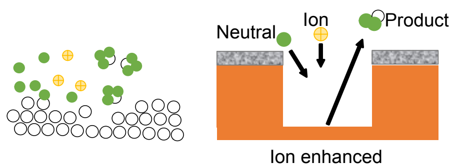

Fig. 19 Ion enhanced etching

4. Combination of etching and passivation (Fig. 20)

If partial passivation gas is added to the etching process, the side and bottom are attached to the side wall during the etching process. Passivation at the bottom is quickly bombarded because of ion sputtering, and the etching continues at the bottom, while lateral wall etching is prevented. The combination of etching and passivation can achieve excellent anisotropy.

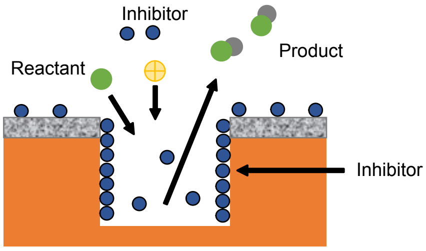

Fig. 20 Etching and passivation

Different gases are selected for different etching materials in dry etching. The selection of etching gases depends mainly on the etching material, requirements of the etching rate, selection ratio, and anisotropy. Table 1 shows the relationship between etching material and etching gas in dry etching.

Table 1 Etching materials and gases in dry etching*

Etched material	Chemical gases (multiple choices)
Monocrystalline silicon	CF_3Br, HBr/NF_3, SF_6/O_2
Polysilicon	$SiCl_4/Cl_2$, BCl_3/Cl_2, $HBr/Cl_2/O_2$, HBr/O_2, Br_2/SF_6
Al	$SiCl_4/Cl_2$, BCl_3/Cl_2, HBr/Cl_2
Al-Si-Cu, Al-Cu	BCl_3/Cl_2+N_2
W	SF_6, NF_3/Cl_2
TiW	SF_6
WSi_2, $TiSi_2$, $CoSi_2$	CCl_2F_2/NF_3, CF_4/Cl_2
SiO_2	CCl_2F_2, CHF_3/CF_4, CHF_3/O_2, CH_3CHF_2
Si_3N_4	CF_4/O_2, CF_4/H_2, CHF_3, CH_3CHF_2
GaAs	$SiCl_4/SF_6$, $SiCl_4/NF_3$, $SiCl_4/CF_4$
InP	CH_4/H_2
Photoresist	O_2

* Reproduced from Cui (2005)

In recent years, with the drive for device development and the progress of technology, the dry etching process for specific materials and devices has been developed. They include the Bosch process for silicon materials, high frequency of 40-MHz etching for GaN materials, high-depth-to-width-ratio nanometers based on the Bosch and mask transfer technology, column structure (Fig. 21), spiral pitch structure (Fig. 22), and a very slow GaN etching process at a rate of 1.6 nm/min (Fig. 23).

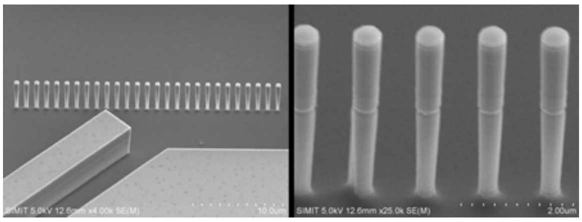

Fig. 21 Nano-scale structure with a high depth to width ratio

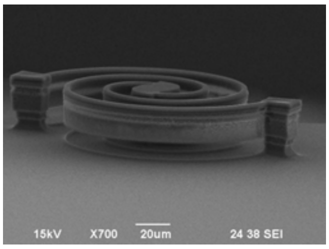

Fig. 22 Spiral structure

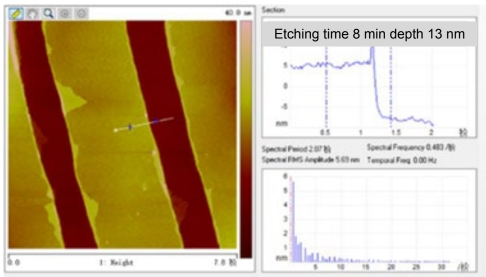

Fig. 23 Extremely slow etching process of GaN

4.3 Thin film deposition technology

Thin film deposition is an important part of optoelectronic devices, and includes Ohmic contact for devices, Schottky contact metal electrodes, transparent conducting electrodes, and silicon oxide and silicon nitride for passivation and isolation, which are used to change the optical transmission characteristics of devices, such as reduced reflection films on the surface of devices, waveguide devices, and preparation of the waveguide layer. Thin film deposition is generally divided into two categories: physical vapor deposition (PVD) and chemical vapor deposition (CVD). In the optoelectronic device process, PVD technology generally includes thermal evaporation, electron beam evaporation, and magnetron sputtering. It is widely used to grow all kinds of metal films, functional materials, and dielectric materials. CVD generally includes PECVD and LPCVD, which are used mainly to grow a film in the passivation layer.

Given the new problems arising in scientific research and industry, preparation technology for thin films has been greatly promoted and developed; for example, adding ion source assisting deposition to make thin films by evaporation has compact characteristics, and a magnetic field to make a film by sputtering has a little damage and improves the surface quality of the sample. The introduction of inductively coupled plasma chemical vapor deposition (ICPCVD) technology has led to the growth of high density silicon oxide and silicon nitride films at low temperatures, and inclined deposition technology has opened up a new way to prepare thin films, which can make the thin films form any shape at the growth stage. This is different from the optical properties of traditional films (Fig. 24).

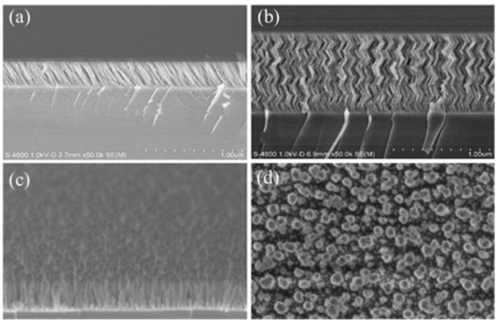

Fig. 24 Silicon oxide films prepared by electron beam evaporation: (a) inclined columnar growth; (b) zigzag growth; (c) spiral columnar growth cross section; (d) spiral columnar growth surface

4.4 Chemical mechanical polishing, wafer bonding, and ion implantation

Chemical mechanical polishing (CMP) process, through physical and chemical actions, can reduce and polish samples (wafer) or remove various types of materials on the surface of the sample to realize an overall planarization effect, which is an important issue in optoelectronic devices.

Through rational optimization of polishing liquids, polishing pads, polishing head, and pressure settings (Fig. 25), the current semiconductor materials (Si, GaAs, InP, GaN, etc.), insulation materials (SiO_2, sapphire base, quartz glass, lithium niobate, etc.), and metals (Al, Au, Cu, etc.) can achieve good thinning, polishing, and leveling. Fig. 26 shows the glass and silicon mosaic structure (2-nm roughness) and the polishing effect of through hole silicon (4-µm holediameter). Above work was achieved at the Nano Fabrication Facility of Suzhou Academy of Sciences.

Wafer bonding technology can achieve two heterogeneous samples (wafer), i.e., temporary and permanent bondings. Specific technical means can be divided into anodic bondings (glass and silicon), eutectic gold bonding (Au-Au bonding), alloy bonding (AuSn, CuSn, AuIn, etc.), and all kinds of adhesive bonding. In silicon-based optoelectronic integrated chips, one of the ways to realize the on-chip light source (laser) is to bond the III-V epi-taxy onto a Si substrate.

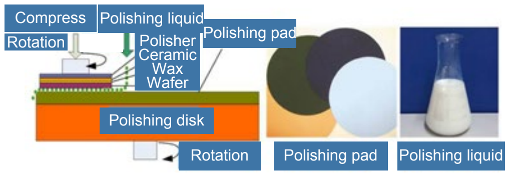

Fig. 25 Elements involved in the CMP process

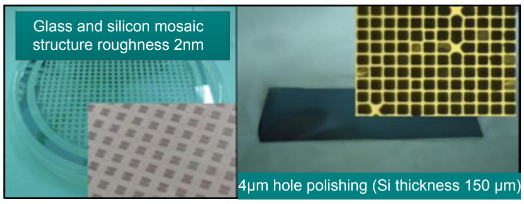

Fig. 26 Glass and silicon mosaic structure (2-nm roughness) and through hole silicon polishing effect (4-µm hole diameter)

Ion implantation is a method to introduce a number of controllable impurities into the substrate by external forces to change the properties of the material. The initial function of the ion implantation process is to form doping in specific regions of the semiconductor. At present, an almost all-element injection process can be realized by enriching the element library, and the double-charge or even three-charge element is injected to achieve ultra-high energy (3 MeV) injection. In addition to material doping, ion implantation has been widely used in the luminescence of silicon-based nanomaterials, surface modification of GaN materials, and substrate stripping (smart cut) technology.

The possible processes involved in the manufacturing, research, and development of optoelectronic devices include cutting, oxidation diffusion, annealing, lead bonding, and inversion bonding. These processes are not described in this study.

5 Development of optoelectronics and technological challenges

5.1 Materials and technologies for discrete devices

Optoelectronic devices are often divided into active and passive devices. Passive devices, such as waveguides, couplers, split wave/combiners, optical switches, and adjustable light failure, usually use silicon as materials. Active devices, such as LDs, PDs, modulators, and optical amplifiers, generally use InP, GaAs, and other compound semiconductors.

Silicon oxide has good performances with low-loss waveguides, and low-voltage silicon oxide has a good performance in low-loss waveguides. Although one company (LioniX) has provided a multi-mesh wafer service with a low refractive index difference box and a high refractive index difference double strip structure, different requirements are needed on the waveguide. Different requirements have been put forward. Designing and processing low-loss silicon oxynitride waveguides to meet the demand is still a problem to be solved. Lithium niobate ($LiNbO_3$) crystals are irreplaceable in high-speed optoelectronic modulators and large photoelectric coefficients, and have good optical transparency in a wide range of wavelengths. Lithium niobate modulator has the requirements of low energy consumption, good modulation speed, and good dynamic range for its waveguide technology, electrode process, and bonding process. Higher requirements have been put forward. Yttrium iron garnet (YIG) single crystals are the only choice for commercial optical isolators. Although each discrete device is becoming more mature due to the growth of the materials field, processing technology, and device performance, the discrete components of different materials are integrated into or on the same substrate, and many functional devices are realized at the same time. There are many structural and technological problems to resolve (Chen et al., 2013; Haney, 2013).

5.2 Photon integration technology

Photon integration is the basis for full play of the photon bandwidth and energy consumption. Various devices need to be integrated on a substrate to complete different functional modules. Silicon-based photons can be integrated with mature CMOS technology and combined with heteroepitaxial germanium detector technology, to realize photonic integrated receiver chips. However, in silicon-based photonic integration, the focus of the research is still the solution for the light source and high-performance silicon-based modulator. Photonic integrated chips based on InP substrates have been applied to high-speed and high dynamic range systems, and the advantages of high performance light sources on the InP substrate and the electro-optic modulator based on field effects have brought strong power for photon integration based on the InP substrate. Reducing transmission loss of the InP base waveguide and reducing the cost of the InP substrate have been hot topics.

With the continuous updating of the optical interconnection technology and the silicon-based photoelectron technology, it is very important for all optical communications on the chip and the interconnection of on-chip photonic devices to use active luminescent media and silicon-based waveguide devices to integrate the on-chip hybrid light source. At present, hybrid integration may be an important trend in the development of photonic integration technology. This technology will have different functions and chips of different materials, such as the III-V laser and lithium niobate modulator. Based on the bonding technology, a monolithic integrated photonic chip has been realized (Liang and Bowers, 2008; Cai et al., 2013; Heck et al., 2013). Among these technologies, the hybrid integration of laser and silicon substrate is one of the most effective and practicable schemes for realizing silicon-based lasers. There are two main ways to realize silicon-based hybrid lasers at present. One is to direct the light emitting materials directly on the substrate, such as that achieved by Qin Guo's group at Peking University, with a silicon-based bonding laser, which is realized by the selective metal bonding technology or by etching the DBR grating on the silicon waveguide; thus, a single mode on the silicon base is obtained (Yuan et al., 2015). The other way is the end butt coupling laser, which is coupled mainly by end butt coupling. The optical field is coupled with active light emitting materials and passive waveguide devices. The fabrication precision and process requirements are generally high. At present, these monolithic integrated photonic chips still face many technical challenges, such as micro-complex structures and precision packaging between chips; thus, these chips are more dependent on a complete and advanced optoelectronic technology development platform to solve these problems.

5.3 Integration technology of optoelectronic and electronic devices

Simultaneous integration of photonic and electronic chips on the same chip is an ultimate goal of the industry. It is a way to decrease chip costs and energy consumption and improve transmission bandwidths. Optoelectronic integration requires simultaneous optimization of photon and electronic functional units on the same substrate material, and there are problems in design, process compatibility, and so on. In recent years, with the joint efforts of industry and scientific research, important results have been achieved. For example, with the help of AIM photonics, researchers at the MIT and UCSB developed a chip that integrates electronic components and optical elements on the same silicon layer. In addition to the millions of transistors used to perform computing, the chip consists of a modulator, a waveguide, a filter, and a photodetector, which is required for the optical chip (Atabaki et al., 2018).

In addition, advanced packaging technology based on glass through holes has a low-loss factor, low production cost, and excellent optical and electrical properties. It can be applied to the interconnection of optoelectronic chips which can effectively decrease size and chip loss and improve chip speed. It has become a technology worthy of attention in the pre-electronic packaging technology. The advantage of through glass via (TGV) technology in RF and microwave devices is gradually being confirmed due to its excellent high-frequency transmission characteristics. For example, Menlo Micro recently joined Corelle to create wafer-level bonding in a TGV 8-inch RF MEMS wafer. Two companies jointly released the successfully integrated glass through-hole packaging technology to extend Menlo's high-performance RF and power products to ultra-small wafer-level packaging. However, this technology still faces many challenges. For example, there are a variety of processing methods, such as laser ablation, photosensitive glass, and dry etching, in the pore forming of TGV, but the technical problems, such as the side wall quality and depth-width ratio of the through hole, need to be studied in depth, and the solution to these questions needs to be strongly dependent on the photoelectrons.

In recent years, submicron array graphic technology has attracted increasing attention. A periodic dot matrix or aperture array formed on the surface of the substrate is used to reduce the loss of light and improve the luminous efficiency. As one of the graphic structures of the array, grating structure is the core component of optical sensors and spectrometers, and it has an irreplaceable role in the optical devices. For example, high sensitivity polarization imaging technology is the product of combination of polarization detection technology with imaging technology. By analyzing the polarization information images, much information about the target can be obtained. Effective detection and recognition of target objects used in complex environments are important in the fields of optical communication and display. Regarding the use value, compared with traditional polarizing devices, new polarizing devices and technologies developed in recent years combined with charge coupled device (CCD) cameras can be used for fast, stable, and high-precision imaging. The core structure of the new polarization devices is based on different orientations of the micronano metal gratings, and one of the major technical challenges is to make the structure of the nano metal grating at a high depth to width ratio. Therefore, there is a great challenge and an important opportunity in the development of these new optoelectronic devices to efficiently fabricate large-area periodic nanostructures. In recent years, with the rapid development of semiconductor micro- and nano-scale processing technology (such as high-speed electron beam exposure, holographic lithography, plasma etching, and chemical vapor deposition) and related common platforms, new generation optoelectronic devices and technologies represented by highly sensitive polarization imaging technology have been developed.

5.4 Driving force of industrial development

Chips with different functions continue to transmit data between them. If electronic signals are transmitted with copper wires, even if the chip processing capacity continues to increase, a bottleneck will still occur due to the limited transmission of the wire data, which leads the chip to have to wait a long time to send and receive data (Gunn, 2006; Asghari and Krishnamoorthy, 2011). This is the bandwidth bottleneck caused by electronic inter-connection, and an optical interconnection can solve this problem, providing a powerful impetus for the electronic chip giants to develop optoelectronic integrated chips. In the field of optical communication, wavelength division multiplexing (WDM) systems with discrete devices have not only disadvantages of high encapsulation cost and large system power consumption, but also poor system reliability. Optoelectronic integrated chips can decrease the volume and power and improve the stability of network connections. This is the product that data centers and optical communication equipment providers have been looking forward to. With the increasing amount of information, the interchip optical interconnection of super bandwidths and low energy consumption of the light exchanges have provided a strong impetus for the development of optoelectronic integration technology (Atabaki et al., 2018; Bogaerts and Chrostowski, 2018).

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