Recent developments in silicon optoelectronic devices

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Abstract

Due to the rapid growth of the internet and multi-media communication networks, there are urgent needs and tremendous commercial values in the development of optoelectronics integrated circuits (OEICs). This work reviews the recent developments and the prospect of silicon-based integrated optoelectronic circuits (Si-OEICs). The technological aspects of porous silicon and oxynitride devices for integrated optoelectronic applications are discussed. Some optoelectronic devices being realized with these technologies are described. Recent achievements indicate that the present constraints for using Si-based materials in optoelectronics are mainly technological rather than physical. Once these technological difficulties are resolved, the realization and applications of Si-OEICs will grow rapidly.

1. Introduction

Although the aspiration of “computation at the speed of light” may still be several light-years beyond our present technological frontier, the optoelectronic system integration has already come to light [1–9]. There are urgent needs and tremendous commercial values for the development of optoelectronics integrated circuits (OEICs) for the globally rapid growth of the internet and multi-media communication networks in recent years. Several attempts have already been made. silica-based planar lightwave circuits (PLC) for fiber-matching have been developed [1–3]. These integrated circuits provide various components for fiber-to-the-home (FTTH) [4,5] optical networks and wavelength-division-multiplexing (WDM) transmission networks [6–8]. Integrating the semiconductor laser with the microcavity for wavelength tuning has also been attempted [9]. However, these OEICs are still very primitive and the costs are still very high. Unlike the microelectronic systems where all the components are built on a single material—silicon, the photonic components often require some incompatible materials. For example, light sources are often built on compound semiconductors and waveguiding parts are built on LiNbO3 film.

Using silicon-based materials, e.g. oxide or silica, nitride, oxynitride, and porous silicon as well as the microfabrication technology will be a promising technology for integrated optics. There are many merits for Si-OEICs. Since the mainstream electronic devices, microprocessors, and memory are made of silicon, fabricating optoelectronic devices on silicon is the most cost effective way for electro-optic system integration. In addition, silicon technology has the following attributes. It is the greatest and most mature technology available to date. It could be as fine as nanometer in structure and as great as a giga scale in complexity. With silicon technology, we can make any kind of geometries, e.g. optical cavity, 3D and motion structure, nano structures. With nano geometry, even the quantum effect is possible in Si. On the other hand, silicon is the largest (as large as 30 cm in diameter) substrate available. It is particularly suited for large-scale integration and mass production with excellent uniformity and reproducibility.

Silicon material is now also possible for use in light generation. Silicon was not used for light-emitting devices (LEDs) as it is a non-direct band-gap material. However, quantum confinement of electronics and holes are found in quantum dots and nanocluster silicon structures [10,11]. On the other hand, strong...
luminescence can also be generated from the radiative centers in silicon oxide and nitride [12–15]. A lot of investigations on the luminescence properties of silicon-based structures, including porous silicon (PS) [10, 16,17], silicon nanoclusters in amorphous SiO 2 [11,18–21], have been conducted. A wide range of luminescence, including red-orange band (luminescence peak with energy 1.6–2.0 eV) and blue band (2.6–2.8 eV) in these structures were observed. A green line has also been found by making use of the silicon nitride (Si 3N 4) structure. This provides the possibility for fabricating full-color devices based on the silicon technology [11].

In guided wave applications, the silicon-based devices have features of low insertion loss, polarization-independent behavior and efficient fiber pigtails. Since silicon is a low-contrast material, a high-efficiency fiber-chip coupling can be obtained [3,4]. The successful development of microfabrication technology for nanoscale structures will also have a great impact on optoelectronics. Optical systems in the past have been bulky with expensive optical components like mirrors, filters, beam splitters. These components require precise alignment in the micron scale. By employing the microfabrication technology, optical microelectro-mechanical systems (MEMS) are possible and the size of the present optical system can be reduced greatly [9]. Thus the Si-based optoelectronics have features of low cost, high robustness and multifunctional. This leads to a bright future for low-cost mass production of OMEMS and OEICs.

2. Silicon oxynitride

2.1. Luminescent properties

Applications of silicon oxynitride in various integrated optical devices have been attempted [12,22,23]. The luminescence of the silicon nitride and SiO 2 can be due to the radiative centers. Different centers will produce different luminescence bands [12]. Table 1 shows the various defect centers in oxide and nitride [12]. The luminescence bands, ranging from red band to UV, depend on the defect types. The applications of these radiation centers in LEDs need to be explored. Particular attentions should be placed on the enhancement of luminescence intensity and extending the lifetime of photon.

Quantum confinement is also possible in dielectric films with silicon dots/nanoclusters [18–21,24–29] and it was suggested that Si nanocrystals embedded in silicon oxide are potential candidates for Si-based LEDs. Several methods, including sputtering, chemical vapor deposition and ion implantation were proposed. A model for the quantum confinement mechanism was also proposed [11]. It has been suggested that the SiO x film consists of five different tetrahedral \( \text{Si}_v \text{O}_{4-v}, \ (v = 0, 1, 2, 3, 4) \). That is, the SiO x may appear in the following phases: SiO 2, Si 2O 3, SiO, Si 2O, and Si. As a result, the band gap may vary from 1.1 eV (Si) to 8.0 eV (SiO 2). The spatial fluctuation of the chemical composition in SiO x leads to the formation of potential wells where carrier confinement occurs. However, there are some constraints for the application of silicon oxide based luminescence materials. According to the band structure, the field strength needed for electroluminescence in SiO x will be larger than 6 MV/cm for electron injection and more than 10 MV/cm for hole injection from Si into the SiO 2. This field strength is very close to the breakdown field of silicon dioxide. This constraint can be resolved by employing the SiN x structure, which has several potential advantages over the SiO x structures. It is well known that the band gap of Si 3N 4 is 4.6 eV. The barriers at the Si–Si 3N 4 interface are 2.0 and 1.5 eV for electrons and holes, respectively. Hence for bipolar (both electron and hole) injection, a field strength of 2–4 MV/cm is enough in silicon nitride. This field strength is much lower than the breakdown field (~9 MV/cm) of silicon nitride. Silicon nitride also contains a high density of electron and holes traps, which will result in a strong trapping of electrons and holes. Consequently, the injection current of nitride is of 5–8 orders of magnitude larger than that of SiO 2. Hence the electroluminescence intensity in SiN x should be larger than that in SiO x because of the larger injection current. Of course, actual luminescence intensity in these structures will be governed by the density of non-radiative defects. Fig. 1 illustrates the quantum wells formed in silicon nitride with silicon nanoclusters [11]. Fig. 2 shows a typical PL in silicon nitride with several different Si contents [11].

2.2. Waveguide properties

Various waveguide devices were fabricated using silicon oxynitride [22,23]. Silicon oxynitride films can be deposited using various methods. The most popular ones are: low-pressure chemical vapor deposition (LPCVD) and plasma-enhanced chemical vapor deposition (PECVD). The refractive index and absorption
loss of oxynitride films are governed by chemical composition and the deposition process. Fig. 3 shows the refractive index of oxynitride films with different compositions. Thin films prepared with conventional LPCVD and PECVD can have an optical loss as low as 0.2 dB/cm in the visible range of light [22]. At wavelengths around 1500 nm, the optical losses increase remarkably. This degradation is mainly due to vibrational overtones of the \( \text{N—H} \) and \( \text{Si—H} \) bonds. It was reported that both the hydrogen content and the absorption loss can be reduced greatly by post-deposition annealing at high temperatures [22]. Thus hydrogen content is the major constraint for 1500 nm applications. Hydrogen is the main chemical impurity in oxide because of residual moisture during oxidation [12]. For oxynitride prepared by LPCVD and PECVD methods, additional hydrogen from the gas sources will be incorporated.

To overcome these drawbacks, re-oxidizing the LPCVD Si-rich nitride layer was proposed [30], secondary ion mass spectroscopy (SIMS) study reveals that the hydrogen content of nitride film can be reduced by more than 40% (as shown in Fig. 4). A thin silicon nitride or silicon-rich nitride layer was deposited on the thermal oxide using LPCVD with SiCl\(_4\) and NH\(_3\) chemical sources. The samples were then re-oxidized at 1000 °C for 35 min. It is found that a large number of hydrogen impurities are introduced by the LPCVD process. Stoichiometric silicon nitride (sample B) has the highest hydrogen content. Silicon rich samples have lower amounts of hydrogen. For Si-rich samples with re-oxidation (sample F), the hydrogen content decreases by more than 40%. Si-rich SiO\(_x\)N\(_y\) consists of Si—O, Si—N and Si—Si bonds and the chemical reactions for the oxidation of silicon-rich nitride could be very complicated. However, the key reactions should involve the following process [30]:

![Fig. 1. Energy band diagram of silicon nitride with silicon nanoclusters.](image1)

![Fig. 2. Photoluminescence of Si-rich silicon nitride.](image2)

![Fig. 3. Refractive index of various silicon oxide, silicon oxynitride and Si-rich nitride.](image3)
Reactions (1)–(4) involve in the elimination of hydrogen-containing species which are major origin for the large optical loss of oxynitride waveguide. Thus, the preparation method will offer an excellent oxynitride films for integrated optical devices in 1550 nm wavelength applications. The method for preparing oxynitride by re-oxidizing of Si-rich silicon nitride was proposed for MOS gate dielectric applications. For optical waveguide applications, we need a thick and uniform layer which can be achieved by employing multiple deposition-oxidation steps.

3. Porous silicon

Both light emission and guided wave applications are possible with the porous silicon. PS has been widely studied recently [10,31–35]. Many applications of this material, e.g. LEDs, optical waveguide and photodetectors, have been widely explored [36–38]. It was soon found that porous silicon fabricated on polycrystalline silicon films (so called PPS or porous poly-Si) offers further advantages over conventional PS [36,39]. PPS films can be formed on silicon, oxide, metal, and glass. The PPS films can be deposited over a large area and have a smoother surface and more uniform microstructure than PS, these characteristics are very important for waveguiding device applications where the device sizes are rather large and high uniformity of the core layers are needed. However, many issues have associated with the conventional electrochemical anodization method. The wet etched surface was found to be instable and non-uniform. In addition, the wet etching process also introduced several reactive residents which could contaminate the prepared film and other IC fabrication processes.

3.1. Luminescent properties

Electrically induced visible luminescence in PS films has been demonstrated [37]. However the efficient of electro-luminescence in PS-based devices is still too low to have any practical application. Another problem blocking the PS applications in LEDs is the instability. Ageing phenomenon occurs when PS devices are exposed to the ambient.

Indeed, the surface properties of porous silicon have profound effects on the characteristics of optoelectronic devices. As the surface layer is very unstable, the reliability of the devices is still one of the key problems. The quest for solutions to these issues is of great theoretical and practical importance. We have developed a new method to produce porous polysilicon films (PPS) by plasma etching of the thermally oxidized polycrystalline silicon films. The major advantage of the plasma etching technique is that a native and stable silicon surface of the micropores can be obtained.

Regarding the light-emitting mechanism in porous silicon, several theories have been proposed to explain the experimental phenomena [10,34–38]. Some believe that the light emission in PS is due to quantum confinement of two-dimension sheets, one-dimension wires or zero-dimension dots of silicon crystal with nanosizes [10]. Some believe that the light emission phenomenon in PS is due to the radiative centers in silicon or silicon oxide [38] and there are more and more researchers believe that the experiment observed light emission in porous silicon is due to the confinement of carriers from the defects in the oxide [40]. There are still many debates. We have studied the luminescence effects in PS and PPS films prepared by several different methods or with different treatments [38,39] and we are inclined to believe that the luminescence in porous silicon is related to the defect centers in the surface silicon oxide layer.

Figs. 5 and 6 show the photoluminescence spectra of PS and PPS film in the visible and ultraviolet region.
respectively. To produce porous structure, a standard anodization process was carried out in the HF(49%): ethanol 1:1 solution at a constant current density of 10 mA/cm² for 5 min. For porous polysilicon samples, a polysilicon layer of 600 nm thickness was first deposited and doped. Same anodization conditions as the porous silicon are used to produce the PPS films.

To investigate the properties of this thin surface layer and its effects on other properties, we remove the surface layer by reactive ion etching (RIE) in plasma chamber with pressure of 50 mTorr.

For PS film, a band centered at around 680 nm or 1.82 eV is found. Where for PPS samples, two bands, centered at 400 and 680 nm, are found. There is a general trend for both PS and PPS films that the peak intensity decreases remarkably as the plasma etching proceeds. However, the energy location of PS films almost remains unchanged. The 400 nm (3.1 eV) peak disappears when the surface oxide layer was completely removed. These observations cannot be explained with the quantum confinement model. First of all, if the PL is due to quantum confinement, there should be no difference between the PS and PPS samples in the energy locations. According to quantum calculation the upper limit of the silicon nanoparticles size is about 3 nm [40]. It seems that the difference in the particle sizes of PS and PPS films should not have such significant difference for size less than 3 nm. Secondly, the surface etching should not lead to a significant reduction in PL intensity if the peak locations does not change and when the etching takes place on the oxide layer only (samples PS1 and PPS1). Thirdly, multiple peaks due to the transitions between different energy levels of confined states and wider ranges of PL bands are expected due to the distribution of silicon nanocluster sizes [17]. We assign the 1.82 red band to the luminescence center in silicon oxide. In glassy oxide, it is well known that the PL band at 1.9 ± 0.1 eV range is due to the R center or non-bridge oxygen hole center (NBOHC). The location of this center depends on the excitation wavelength and normally varies from 1.8 to 2.0 eV. The formation of NBOHC can be due to the breakdown of hydrogen bond in Si–O–H, the breaking of peroxy linkage (Si–O–O–Si) and the incomplete oxidation of intrinsic paramagnetic E’ center on the etched surface layer of silicon. In some cases, e.g. irradiation, high field stressing, breaking of stressed Si–O–Si linkage to form the NBOHC is also possible. These mechanisms are formulated as followings:

$$\equiv Si \cdot (E’ center) + O \rightarrow \equiv Si–O.$$  \hspace{1cm} (5)

$$\equiv Si–O–Si\equiv \rightarrow Si–O \cdot + \equiv Si.$$  \hspace{1cm} (6)

$$\equiv Si–O–O–Si\equiv \rightarrow 2\equiv Si–O.$$  \hspace{1cm} (7)

$$\equiv Si–O–H \rightarrow \equiv Si–O \cdot + H.$$  \hspace{1cm} (8)

Without further treatment, reactions (5)–(7) could be the dominate mechanisms for generating NBOHCs in anodized porous films. On fresh etched silicon surface will distributes a lot of silicon dangling bonds (E’ centers), these bonds will capture oxygen to form NBOHCS (reaction (5)) or forming oxide networks.
The second PL band in Fig. 6 is ascribed to other radiative center in the oxide layer. The small peak around 2.8 eV (440 nm) can be attributed to the triplet–singlet transitions in a two-coordinated Si defect ($\equiv$Si) in surface silicon oxide layer. The 3.1 eV peak should be due to the antibonding–bonding orbits of the singlet–singlet transition in $\equiv$Si–Si$\equiv$ bonds or O vacancies in the oxide layer. This defect is one of the most important defects in silicon oxide [12,41]. Formation of this defect can be due to the breaking of two Si–O bonds and forming a single Si–Si bond or the bonding of two adjacent E$'$ centers; namely,

$$\equiv\text{Si}–\equiv\text{Si} \rightarrow \equiv\text{Si}–\text{Si} + \text{O} \quad (9)$$

$$2\equiv\text{Si} \rightarrow \equiv\text{Si}–\equiv\text{Si} \quad (10)$$

These experimental results provide new information to better understand the radiation phenomena in these films. For the application point of view, it is expected that the oxide or nitride based LEDs will have better properties than those of the PS LEDs as the luminescence in porous silicon is related to the defect centers in the surface silicon oxide layer.

3.2. Waveguide properties

In optical waveguide applications, the porosity of the PS film should be uniform and the surface should be stable. However, many issues have associated with the conventional electrochemical anodization method. The wet etched surface was found to be instable and non-uniform. In addition, the wet etching process also introduced several reactive residents which could contaminate the prepared film and other IC fabrication processes. Finding a new approach to overcome the above drawbacks has become an important and indispensable work in the PS optoelectronic research. A dry etching method was proposed [39]. By etching back the as-oxidized polysilicon using reactive ion, a uniform porous structure was formed. Process detail can be found elsewhere. A poly-Si layer of 7000 Å thick without any doping was first deposited by thermal decomposition of silane gas (SiH$_4$) at 625 °C for 50 min. Thermal oxidation of the as-deposited poly-Si film was performed at 1000 °C for 50 min in dry O$_2$ ambient. The surface oxide thickness is about 500 Å whereas a thicker oxide layer was formed in the grain boundary region as the oxidation rate on the grain is significantly lower than that at the grain boundary for heavily doped polysilicon. The non-uniform oxide thickness act as “self-align mask” for reactive ion etching (RIE) and pores will be formed in the grain region after the etching. The proposed new technique does not need any additional photolithographic masking step or additional electrode and chemical solution.

Fig. 7 depicts the morphology of sample being etched for 3.5 min. A porous structure with pores with diameters in the range of 200–300 nm were formed. Around the pores are the grain boundaries where the oxide layers are thicker and cannot completely removed with 3.5 min plasma etching. Fig. 8 shows SEM images for samples being etched for 4.5 and 5 min. Significant changes of surface morphologies are observed. The pore edges of the sample become smoother as further etching will result in the removal of the remaining oxide layer around the grain boundaries and the etching is not longer highly selective. The pore walls become “thicker” as the sharp regions on the surface were etched away. After 5.0 min etching, all the oxide and polysilicon films should have been removed and the image depicted in Fig. 8(b) should be the surface morphology of crystal silicon substrate with trace amount of silicon oxide or a thin layer of native oxide.

Compared to the morphologies of PS films prepared by other methods, the present method can produce a much uniform PS and PPS film in a large area. In addition, the process is simple and compatible with the Si microfabrication technology. These results are particular important for waveguide applications. Since the refractive index of this material is governed by the porosity, the porous silicon can be used as either as core

![Fig. 7. (a) SEM morphology of the as-oxidized polysilicon film being dry etched for 3.5 min; and (b) Fine structure of the micropores in (a).](image-url)
material or cladding layer of an optical waveguide depending on the porosity. Arrand et al. [42] found that the refractive index of porous silicon can be tailored in the range of 1.3–1.8 for wavelength of 1.1 μm.

4. Some optoelectronic devices

In the past few years, several attempts for making optical devices using microelectronics fabrication technologies have been made. Although some of them are still very primitive, we believe that their characteristics can be improved with modified designs, deposition process and other technological processing steps like lithography and etching. Here we describe briefly some of the designs. More details can be found in the references.

4.1. Waveguide design

Optical waveguide based on PECVD oxynitride was investigated extensively by the Twente group [22,23]. Fig. 9 shows a basic design of oxynitride waveguide. An oxide layer was first grown thermally then the cladding and the core layers were deposited. The core of the waveguide is an oxynitride layer with $n_{TE} = 1.4825$ and $n_{TM} = 1.4846$. Silicon nitride is used for the birefrin-

gence compensating layer (BCL) which has $n_{TE} = 1.9814$ and $n_{TM} = 1.9729$. The cladding is made use of silicon oxide with $n_{TE} = 1.4633$ and $n_{TE} = 1.4642$ [22].

4.2. Optical wavelength filter

An optical fiber carries a number of signal in different wavelengths in WDM networks and requires add-drop multiplexers to extract signals. Mach–Zehnder Interferometers (MZIs) structure using silicon oxynitride waveguide was fabricated for this purpose (Fig. 10) [22]. A more complicated multiplexer–demultiplexer can be realized by cascading some unequal branches [7]. A PPS-based add-drop wavelength filters, operating at 1550 nm wavelength was also designed and fabricated (see Fig. 9).
4.3. Non-linear waveguide

Non-linear waveguide can also be fabricated using oxynitride. Fig. 11 shows the cross-section of non-linear waveguide. A window was open firstly by chemical etching on the top cladding oxynitride and then polymer for non-linear waveguide is deposited [24]. By choosing the refractive index of the top oxynitride cladding identical to that of the polymer, a relatively large field can be extended into the non-linear polymer.

4.4. Light emitting diode

Porous silicon based LED was fabricated [37,43]. However, the electro-luminescence efficiency is too low (about 0.2%) to have practical application. The main reasons for the much lower power efficiency are the difficulties in injecting carriers from the contact into the PS and the poor transport properties in PS. Since the blue PL has a measured lifetime of 1 ns [44], blue PS LEDs is not suited for display but is still useful in optical interconnects. However, much more work remains to be done in this area. Since the blue luminescence is believed due to the defects in the oxide, luminescence efficiency can be improved with the silicon oxide and silicon nitride structures [11]. In addition, good contacts and high current injection density can be achieved with silicon nitride based LED.

4.5. Microresonator

With the silicon microfabrication process, microcavities can be fabricated on silicon. These microcavities have many applications in optics. A microcavity coupled to straight channel waveguides was designed by Blom et al. [45]. This microcavity resonator can be used as channel dropping filters in WDM systems.

4.6. Tunable laser based on microcavity

Microelectromechanical system (MEMS) can also be realized with the silicon microfabrication technology. Fig. 12 shows the schematic diagram of the deformable membrane vertical cavity the tunable laser. This structure is similar to that proposed by Larson and Harris [9]. A microcavity is fabricated using the microfabrication technology. The length of the cavity is adjustable with a deformable membrane based on silicon nitride. Together with the silicon quantum dots, a continuous range of tunable laser can be achieved.

5. Concluding remarks

The rapid growth of the internet and multi-media communication networks have called for urgent needs of the development of optoelectronic integrated circuits (OEICs). Silicon-based will have high potential because of many technological merits. This work reviews the recent development and prospect of silicon-based integrated optoelectronic systems. The technological aspects of porous silicon and oxynitride and silicon quantum devices for integrated optoelectronic applications are discussed. Some optoelectronic devices being realized with these technologies are described. The recent achievements indicate that the present constraints for using Si-based materials to optoelectronics are mainly technological rather than physical. It is also noted that integrated optoelectronics is a new area and most of the devices, particularly those realizing with these new fabrication technologies, are still to be invented.

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References

[34] Xiao Y, Heben MJ, McCullough JM, Tsuo YS, Pankove TI, Deb SK. Enhancement and stabilization of porous...


