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Deposited amorphous silicon-on-insulator technology for nano-photonic integrated circuits

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ABSTRACT

Low-loss deposited amorphous silicon (α-Si:H) layers for nano-photonic integrated circuit have been prepared using complementary-metal-oxide-semiconductor (CMOS) compatible technology. Waveguide loss as low as 3.45 dB/cm is reported for films deposited at a low temperature (300 °C) using plasma enhanced chemical vapour deposition process. The influence of the deposition parameters such as gas dilution, plasma power and pressure on the quality of the deposited material is thoroughly characterized using Fourier transform infrared spectroscopy (FTIR), spectroscopic ellipsometry, X-ray diffraction and atomic force microscopy. We show that the optical quality of the deposited film can be directly assessed from distinct frequency bands (2090, 2000 and 840 cm^{-1}) using FTIR, without the need for further waveguide loss measurements.

1. Introduction

Silicon photonics is maturing as an integrated photonics technology platform suitable for various applications. One of the main driving forces behind this development is integration with complementary-metal-oxide-semiconductor (CMOS) technology for next generation high performance computing and data communication. The high-refractive index contrast of silicon with respect to its cladding layers (SiO_2 or air) helps to increase the device density by up to 6 orders of magnitude from traditional silica based photonic circuits. However, further scaling down is limited by the wavelength of light. In order to increase the device density further vertical integration of photonic circuits should be exploited.

Although silicon photonics has made tremendous progress, it has mostly relied on crystalline silicon-on-insulator technology. In spite of the superior material quality, this seriously limits innovation and integration options. It does, for example, not allow for multilayer photonic circuits and also limits the options for integrating electronic and photonic circuits. Various options have been proposed for both these applications, including free space optics but no general consensus has been reached yet. The two main integration routes explored are bonding [1,2] and layer stacking approaches (back-end) [3,4]. Although such 3D integration technologies are widely explored for electronic–photonic integration, a simple CMOS back-end compatible layered approach would be suitable for most applications, including multilayer photonic integrated circuits, and possibly more cost effective.

To realize a layered integration scheme, the main requirement is the availability of a low-loss core material. Over the last few years, the propagation loss of deposited silicon has been brought down considerably, nearly matching that of crystalline silicon. This has been achieved by exploring different deposition techniques. Various groups showed that plasma enhanced chemical vapour deposition (PECVD) is the most suitable technique to achieve low–loss deposited (amorphous) silicon [5–9,11]. The main reason is the ability to deposit layers with a low number of defects. Furthermore, it is an attractive technique for electronic–photonic back-end integration since the deposition can be done at low temperatures (<400 °C). Using this technique propagation losses of 2 and 3.45 dB/cm were achieved for respectively low and high contrast waveguide configurations [8,13] and modulators using thermo-optic [14,12], all-optical [7,15] and electro-optic [16] effects within these layers were demonstrated.

Understanding the material properties is the key for preparing high quality deposited amorphous silicon. Despite improvements over the past years, unfortunately, there is no comprehensive material study available investigating deposited silicon optimized for integrated photonics. As low propagation loss is put forward as the main requirement, unless the material properties are thoroughly studied, it will be impossible to improve the layer quality further. In this paper,

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Table 1
Comparison of different deposition techniques for Si deposition.

Technique	Temperature	Material phase	Loss mechanism
LPCVD	High	α, Poly	Scattering, absorption
Epitaxy	High	Crystalline	Absorption
PECVD	Low	α, Poly	Scattering, absorption
Sputtering	Low	α	Absorption
E-gun evaporation	Low	α	Absorption

α, amorphous; Poly, polycrystalline including nano- and microcrystalline.

we relate the deposition parameters to the material properties of the deposited layers and explain how the latter then influence the propagation loss in the 1550 nm telecom wavelength band.

2. Deposited amorphous silicon

Silicon (Si) can be deposited using different techniques and conditions. Table 1 summarizes different techniques to choose from. The ability to control scattering and absorption loss determines the suitability of a technique for obtaining high quality films. These losses are caused by defects in the material. We can discern two categories of defects. On one hand, hard defects, which cannot be removed from the film; on the other hand, soft defects, which can be reduced after deposition. Material defects such as voids, grain boundaries, dangling bonds and interface defects can be classified as hard defects, while stress and surface roughness are classified as soft defects. The presence of voids and grain boundaries causes scattering of light, while the presence of dangling bonds causes absorption of light. Thus, to achieve low propagation loss, the material should not have grains (i.e. be amorphous or mono-crystalline), should be free of voids and should have a low number of Si dangling bonds.

As previously mentioned (Section 1) the PECVD technique is the most viable technique for low-loss α-Si deposition. One of the main reasons is that the absorption in the electronic bandgap due to dangling bonds can be resolved during deposition by incorporating hydrogen (H) in the Si network resulting in hydrogenated amorphous silicon (α-Si:H). The scattering loss can then be reduced by tuning the deposition conditions to deposit non-crystalline and void free amorphous films. Though hydrogen plays an important role in reducing the propagation loss [17], there is an optimum level above which it plays a negative role.

3. Plasma enhanced chemical vapour deposition

Plasma enhanced chemical vapour deposition is a popular method for thin film deposition in microelectronics. Although mainly used for dielectric deposition it is also used for semiconductor and metal deposition. Fig. 1 illustrates a simple PECVD system with the essential components. By applying a radio frequency voltage across the electrodes, and in the presence of sufficient gas molecules, a plasma is created. The wafer (or substrate) is brought in contact with one of the electrodes to attract the radicals to the surface resulting in film formation. The film deposition and its properties can be tuned by the deposition process parameters: substrate temperature, plasma power, pressure, gas flow and spacing between the electrodes.

3.1. Growth process overview

α-Si:H thin films for photonics are commonly prepared using monosilane (SiH_4) as precursor gas with or without dilution gases such as H_2, He, Ar, and Xe. In the plasma, the precursor gas is dissociated into different reactive species, including silyl (SiH_3), silylene (SiH_2), silylidine (SiH), etc., depending on the energy state.

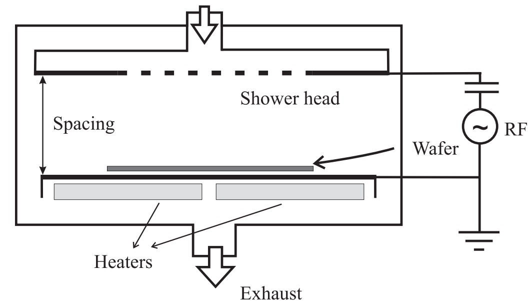

Fig. 1. Schematic of a simple plasma enhanced chemical vapour deposition system.

Table 2
Experimental condition.

Parameter	Range	Nominal setting
RF power (W)	100–300	180
Spacing	500 mils (12.25 mm)	500 mils
Pressure (Torr)	1.5–5	2.6
Temperature (°C)	300	300
Silane (SiH_4) flow (sccm)	100–300	100
Helium (He) flow (sccm)	0–2500	900

These excited species react among themselves and with the feed gas to form a steady state condition to sustain the plasma.

It has been shown by Matsuda et al. [18,19] that SiH_3 is one of the dominant species in the plasma and also one of the major contributors for the film growth. By adsorbing these species on the surface of the wafer a solid film can be formed from the gaseous species. Initially, the wafer surface is covered with –H. When the Si containing radicals arrive onto the H-rich surface it reacts with H, which is then released from the surface (Eqs. (1) and (2)), resulting in a dangling bond. This dangling bond serves as a growth point for further film formation. However, not all of these dangling bonds are further used, hence leaving residual defects. Thus, it is not possible to prepare films without defects (i.e. dangling bonds):

$$\equiv \mathrm{Si{-}H} + \mathrm{SiH_3} \rightarrow \equiv \mathrm{Si{-}} + \mathrm{SiH_4} \tag{1}$$

$$\equiv \mathrm{Si{-}} + \mathrm{SiH_3} \rightarrow \equiv \mathrm{Si{-}SiH_3} \tag{2}$$

3.2. Experimental conditions

α-Si:H is deposited in a 200 mm industrial PECVD deposition tool (Applied Materials Centura 5200). The deposition chamber is a part of a deposition cluster with load-locks. The plasma source consists of two aluminium electrodes separated by a gap set to 12.25 mm. The upper electrode is connected to a radio frequency power supply operating at 13.56 MHz, while the bottom electrode is grounded. SiH_4 and helium (He) are used for film deposition. As mentioned earlier there are a number of parameters that can be tuned to control the film growth. We kept the substrate temperature and the distance between the electrodes (spacing) constant, while the feed gas ratio, pressure, and power were tuned. Table 2 summarizes the experimental conditions of the deposition process used in our experiments.

4. Material characterization

The material properties of the deposited α-Si:H are characterized using the following techniques:

1. Spectroscopic ellipsometry/KLA-Tencor ASET-F5 – thickness and refractive index measurements.