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Infrared photo-resistors based on recrystallized amorphous germanium films on flexible substrates

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ABSTRACT

The fabrication of germanium-based near infrared photo-resistors on a flexible substrate is reported. The devices were fabricated using plasma enhanced chemical vapor deposition of amorphous germanium on an insulating stack layer of silicon nitride and silicon oxide on a flexible polyimide thin film. The deposited films were annealed using a pulsed laser at different pulse rates and laser energy densities to investigate the effects of germanium recrystallization on the characteristics of the photo-resistors. Electrical and opto-electrical responses of the films have been measured and reported. Surface characterization via scanning electron and atomic force microscopy was used to evaluate the variations in surface roughness of the annealed material versus the amorphous germanium layers. Power spectral density analysis was performed to investigate the effect of laser annealing on the crystalline structure of the germanium samples. Providing a low-temperature processing flow, this work lays the foundation for the development of infrared sensors above flexible substrates with potential applications in wearable electronics among others.

1. Introduction

There is increasing focus on developing electronic circuits on flexible substrates due to the designs and implementations that can be translated into new devices and markets. The use of flexible electronics in smart-embedded devices, flexible screens, bio-sensors and wearable optoelectronic devices that can be integrated into clothing is now well underway [1,2]. The flexible approach not only allows for novel design and application, but also has an impact on final product manufacturing costs in large scales [1–3]. In contrast to traditional circuit fabrication on rigid substrates (e.g., glass or silicon wafers), the use of soft or flexible material as substrate allows for roll-to-roll manufacturing processes which can significantly increase production throughput at lower component cost [1,2,4], as well as allow for rapid and low cost prototyping of new devices [5]. Other important factors in use of electronic devices on flexible substrates are the device ductility and conformability [1,5]. The use of flexible and stretchable material allows for designs in which the active region of a device (e.g., photodetector) can be wrapped around corners or be placed in hinges, or other environments where they must endure compressive or tensile stresses which would otherwise damage the devices on rigid anchor substrates [3,6,7]. Today's rapid growth of interest in the internet of things (IoT) also makes it necessary for the flexible and wearable electronics to have fast and reliable compatibility with other components and act as nodes in larger networks. Light sensors are among the most common types of devices needed in a variety of applications, ranging from brightness control to image and video processing. The use of components with response in the near infrared (NIR) region of the spectrum (300 GHz–430 THz frequency band) has shown promise due to the directionality of IR propagation and high sensitivity to low energy density signals [8–10]. Applications for IR and NIR detectors in wearable electronics include motion sensing for context aware wearable devices, flexible physiological monitor for smart military suits, wearable systems for blind-guidance, and flexible temperature sensors for smart health monitoring [11–15].

Silicon has been a prominent choice for the active layer in opto-electronic interfaces in both polycrystalline and hydrogen diluted form. However, in order to detect photons over a broader range of the NIR spectrum, other elements (i.e., group III or V or a com-

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bination thereof) are needed. The use of III–V compounds such as Indium Gallium Arsenide (InGaAs) for NIR detection in optoelectronic components as well as group IV semiconductors such as crystalline germanium are well studied [16,17]. Thin germanium active layers with reduced lattice dislocation densities have shown high efficiencies over a large wavelength range in the near and far infrared. Germanium active layers deposited with low energy plasma enhanced chemical vapor deposition show remarkable low dark current densities which reveal a potential correlation between the defect passivation and dark current decrease. In addition, due to the relatively fast drift velocity of crystalline Ge, germanium based optoelectronic NIR detectors exhibit fast responses which make them ideal candidates for real time applications. However, it has also been shown experimentally that impaired photo-carrier mobility due to an increased number of defect states may contribute to faster carrier recombination and lower current densities [16–18]. As a result, care must be taken with the deposition techniques and the quality of the resulting germanium layer, since defect density will dictate the degree of effectiveness and responsivity of the germanium based devices [16]. Optimum performance is reported when the deposited germanium is mono-crystalline [17,19,20]. Deposition of mono-crystalline germanium however, imposes additional constraints and costs on the overall device fabrication [19]. In contrast, the implementation of poly-crystalline germanium can provide low resistivity with an absorption spectra similar to that of high quality mono-crystalline germanium in the NIR with greater simplicity and at lower cost [20,21]. In addition to its high charge carrier mobility and NIR absorption characteristics, amorphous or poly-crystalline germanium require much lower processing temperatures than silicon, making them a viable choice for applications in flexible electronics [19,22,23]. In this paper, we describe the processing steps to deposit germanium thin films on a flexible polyimide substrate. These films were then annealed using a laser with different processing parameters. Finally, the performance and properties of films processed with different laser powers are studied and compared.

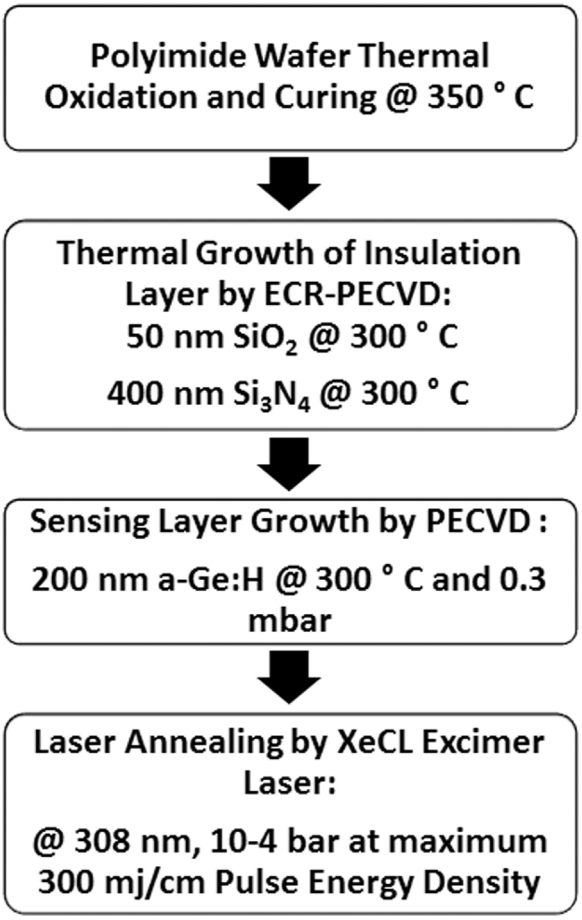

Fig. 1. Process flow for the device fabrication.

2. Device fabrication

The fabrication steps are summarized in Fig. 1. The required layers were deposited on 3" silicon wafers with a layer of thermal oxide on them. The wafers were cured at 350 °C in order to facilitate the deposition and adhesion of a planar polyimide film for the subsequent thin film deposition processes. A 10 μm polyimide insulating layer (PI HD-Microsystem 2611) was spin cast onto the wafers and used as the flexible anchor layer for the NIR photo-resistors. A barrier layer comprising a film of silicon dioxide on top of a silicon nitride layer was deposited by electron cyclotron resonance plasma enhanced chemical vapor deposition (ECR-PECVD). The dielectric layers (SiO_2 and Si_3N_4) were grown at 300 °C with thicknesses of 400 nm and 50 nm, respectively (Fig. 1). The nitride layer was deposited from a mixture of silane (SiH_4), ammonia (NH_3) and helium (He) gases. The barrier layer provides thermal and electrical insulation while improving the adhesion for the NIR sensitive layers on the surface. The sensing layer derived from hydrogenated amorphous germanium (a-Ge:H) was deposited by introducing GeH_4 gas within the PECVD chamber at 250 °C, a working pressure of 0.3 mbar, and a power of 4 W. The final thickness of the a-Ge layer was 200 nm. Existence of hydrogen during the deposition results in thin films with a large volume fraction of nanocrystalline domains. While annealing of these a-Ge:H films is known to enhance both their electronic response and charge transfer properties, conventional thermal annealing using high temperature (>600 °C) furnaces is precluded by the thermal instability of the flexible polyimide support layer. To overcome this limitation, we have investigated the use of various laser annealing protocols to locally recrystallize the material into larger domains, without compromising the quality of the underlying flexible layer.

The a-Ge:H layer was annealed using a Xenon-Chloride (XeCl) excimer laser at a wavelength of 308 nm and dosage of 300 mJ/cm^2 as maximum laser energy density. The XeCl laser at 308 nm has a penetration depth on the order of ~80 nm in the a-Ge films. Therefore, the irradiated energy is efficiently converted to heat, crystallizing the entire germanium film. The laser beam irradiated the sample at normal incidence. After focusing the laser beam with a lens system, a rectangular spot (width: 1 mm, long: 6 cm) was obtained. The excimer laser has a pulse duration of 20–30 ns, which results in a rapid absorption of the energy into the a-Ge:H layer. The relatively poor thermal conductivity of the barrier material confines the thermal budget inside the a-Ge:H, maintaining temperatures below that of the glass transition of the flexible polyimide under-layer (<360–400 °C). The sample was housed inside a vacuum chamber at 10^{-4} bar and mounted on an XY translation stage to allow sample movement and to achieve uniform laser irradiation by overlapping multi-shot scans over the whole surface area of the sample. The final structure is shown in Fig. 2. The processing parameters for the laser annealing process were laser power and the number of laser pulses for each irradiation. Different shots per area as well as different power densities were examined to reach an empirical point where laser annealing produces crystallization of the amorphous germanium films.

Four samples were prepared with different annealing parameters as summarized in Table 1. Samples were exposed to a specified number of laser shots before a new region was illuminated. The rectangular laser spot was raster-scanned across the surface four