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On the formation of silicon wires produced by high-energy ion irradiation

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ABSTRACT

We present a detailed study of simulated and experimentally observed factors which influence the formation of wires in p-type silicon which is irradiated with a high energy, small diameter proton beam, and subsequently electrochemically etched in dilute hydrofluoric acid. A better understanding of the variety of factors influencing wire formation enables a better control of their size, gap between adjacent wires and shape. This addresses a previous limitation in fabricating such structures, such as uncontrollable wire shape and undefined minimum gaps. Furthermore it removes limitations in their application in photonics, such as the difficulty in coupling light between adjacent waveguides, a smearing of the band gap of photonic crystals due to imperfect periodicity, and difficulty in moving the photonic band gap towards near infra-red range. Therefore, the present work allows better control in fabricating components for three dimensional silicon machining and silicon photonics using ion irradiation in conjunction with electrochemical etching.

1. Introduction

A micromachining process has been developed, using high-energy, light ions to induce defects in p-type silicon, which modify the hole current flow in subsequent electrochemical etching in dilute hydrofluoric acid [1–4]. This process has been used for fabricating patterned microstructures in silicon and other semiconductors which similarly exhibit modified etching rates as a result of ion irradiation [5–9]. Many types of ion induced defects act as trap levels where charge carriers undergo recombination, so reducing the hole density and increasing the resistivity [10,11] along the ion trajectories in p-type silicon. From previous studies, the effect of such regions with lower hole density is that the electrical drift hole current flowing through these regions is reduced during subsequent electrochemical etching at moderate or high ion fluences [12] slowing down or completely stopping the formation of porous silicon respectively [3].

The defect production rate of light ions, such as protons and helium ions, with energies greater than about 50 keV peaks close to the end of their range [13,14]. Therefore, this depth region, that is, end-of-range region is consequently most strongly affected when ion-irradiated p-type silicon is subsequently etched. At a moderate ion fluence, only the end-of-range region remains unetched, while the regions above and below it are etched, resulting in formation of a buried silicon wire surrounded by porous silicon. This approach has been used to fabricate multimode waveguides of variable width and height from 1.5 to 3 μm by varying the fluence of 250 keV protons [8,15] and to create three-dimensional patterned surfaces by varying the depth of the end-of-range region by passing the ion beam through a surface mask [16]. By using a combination of multiple energy proton irradiation over a range of 50–1000 keV, and gray-scale masks, different ion penetration depths and multilevel three-dimensional silicon structures can be obtained in a single etch step [4,17,18]. It was also recently shown how free-standing, multilevel wires could be fabricated with curves in the vertical plane using this same process [4]. However, the inability to use this process of ion irradiation followed by electrochemical etching for making gaps smaller than 2 μm was previously discussed [3], which limited further application in fields such as silicon photonics since it precluded the ability to couple light into resonator structures or between adjacent waveguides, where gaps of hundreds of nanometers are required. Besides, the irregular shape of silicon wires formed using this process may induce unavoidable optical losses in waveguides, and perturbs the periodicity of photonic crystals which may smear the photonic band gap [19]. Photonic crystals in [19] have a band gap in the mid-Infrared range, and Ref. [20] discussed how different experimental conditions influence the gap size in more detail. In order to fabricate photonic crystals in the near Infrared or even the visible range, a better understanding of fabricating small wire sizes and gaps is needed.

To address this, a comprehensive study of the related factors and current transport mechanism through and around the

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