Defect enhanced funneling of diffusion current in silicon

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(Received 8 November 2012; accepted 10 January 2013; published online 29 January 2013)

We report a current transport mechanism observed during electrochemical anodization of ion irradiated p-type silicon, in which a hole diffusion current is highly funneled along the gradient of modified doping profile towards the maximum ion induced defect density, dominating the total current flowing and hence the anodization behaviour. This study is characterized within the context of electrochemical anodization but relevant to other fields where any residual defect density may result in similar effects, which may adversely affect performance, such as in wafer gettering or satellite-based microelectronics. Increased photoluminescence intensity from localized buried regions of porous silicon is also shown. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4789849]

Electrochemical anodization of silicon results in porous silicon formation[1,2] used for producing sensors,[3,4] utilizing the photoluminescence properties of porous silicon[5–7] and as sacrificial material for micro-electro-mechanical systems (MEMS) or silicon photonics.[8–10] Electrochemical patterning of silicon may be achieved in various ways, e.g., deeply etched arrays of pores in high resistivity wafers are produced with a wall thickness determined by the space charge region.[11] Modulating the anodization current allows three dimensional fabrication of photonic lattices.[12–14]

The generation of ion induced defects in silicon depends on many factors; typical defects produced are divacancies and other vacancy or impurity-related centres. Many defects act as trap levels where charge carriers undergo recombination. Electrochemical patterning of p-type silicon using high-fluence ion irradiation is achieved by reducing the effective acceptor concentration,[15] resulting in a reduced anodization current by partially or fully depleting these regions.[16,17] Silicon micromachining using high-fluence, high-energy ion irradiation enables the formation of micro- and nano-scale wires, surface and three dimensional patterning,[10,17,18] and components for silicon photonics.[9,19,20] However, the underlying current transport and porous silicon formation mechanism of electrochemically anodized, ion irradiated, p-type silicon has not been completely investigated. A better understanding of such current flow would enable easier formation of nano- and micro-silicon wires and porous silicon structures and applications based on this approach,[9,10,17–20] while also providing valuable insight in all fields related to charge particle irradiation of semiconductor materials, such as in Refs. 21–28.

Here, we report a current transport mechanism observed during electrochemical anodization of ion irradiated p-type silicon, which dominates the total current flowing and hence the anodization behavior in localized areas. It is shown how low-fluence ion irradiation of p-type silicon causes an acceptor doping gradient around the irradiated region. During subsequent electrochemical anodization, this results in funneling of the hole diffusion current along the gradient of modified doping profile towards the minimum doping density which dominates the anodization behaviour. This is observed both for low energy ions where the maximum of the Bragg nuclear energy loss is close to the surface, and for high energy ions where the Bragg maximum is several microns beneath the surface. This phenomenon enables fabrication of porous silicon in selective areas with much higher photoluminescence compared with the surrounding material and reduces cracking problems which may have further applications.[30,31] This study is described within the context of electrochemical anodization but is relevant to other fields where any residual defect density may result in similar funneling effects, which may adversely affect performance, such as in satellite-based devices,[21,22] proton isolation of device areas,[23,24] wafer gettering,[25–27] and ion irradiation of wide band gap semiconductors.[28]

Consider a regime where the defect distribution across the ion end-of-range region is much wider than at the irradiated surface. The most relevant irradiation parameter is the *line fluence* Ψ, i.e., the number of ions irradiating a zero-width line per centimetre of line length.[10] We mainly consider 0.4 $\Omega \cdot$cm (acceptor density $N_A = 4.8 \cdot 10^{16}\,cm^{-3}$) silicon but also demonstrate diffusion current funneling in 0.02 $\Omega \cdot$cm silicon.

Figure 1 shows Atomic force microscope (AFM) images of the etched surface profile for line irradiations with 34 keV He ions, focused to ~1 nm in a helium ion microscope.[29] At low energies, the maximum of the Bragg peak of nuclear energy loss is close to the surface.[32,33] Groups of five lines were irradiated with different Ψ, then the sample was anodized to a depth of ~150 nm with a current density of 60 mA/cm^2 in a solution of 24% HF for 4 s. A line period of 700 nm is sufficiently large to ensure that the lines anodize independently, except for the highest fluence where a larger period was used.

At the lowest fluence ($\Psi = 6 \times 10^7$/cm), there are peaks of ~200 nm full-width-at-half-maximum (FWHM) at the irradiated lines, indicating a lower local anodization current density than that flowing through the surrounding, unirradiated silicon, consistent with the defects deflecting away the anodization current.[16,17] While a similar peak width is

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