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Short Communication

Sub-100 keV ion beam generation with a Van De Graaff accelerator using an external DC voltage supply

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ABSTRACT

We present a method to produce stable proton and helium ion beams with energies of 10–100 keV from a 30-year-old Van De Graaff accelerator using an external stabilized DC voltage supply instead of the belt charging system. Requiring no other modifications, this makes an ideal system for ion irradiation with fluences up to 10^{15} ions/cm^2. Such ion energies and fluences are required in the emerging fields such as silicon micromachining using ion irradiation and we give examples of structures created with sizes as small as 200 nm.

1. Introduction

Fundamental research frontiers in nuclear and particle physics have shifted well beyond the energies available using small, mega-volt accelerators, which are now mostly used for materials analysis using ion beam analysis (IBA) and nuclear microscopy, as well as surface modification of materials by ion irradiation and implantation [1]. For most applications, light ions of a few MeV have traditionally been used in IBA and nuclear microscopy, while ion implantation usually involves heavier ions of keV energies. In recent years however, there has been interest in the research of medium energy (10 keV–1 MeV) ion irradiation, particularly on nanostructures such as quantum dots [2,3], carbon nanotubes [4–6], as well as graphene [7–9]. Medium energy ions can also be used for fabrication of near-surface nanostructures in silicon by direct write, or using a patterned irradiation mask, with subsequent electrochemical etching [10], even though MeV ions are traditionally used [11–13].

In this paper, we demonstrate a simple way to modify a 30-year-old single-ended Van De Graaff (VDG) accelerator to produce a stable sub-100 keV ion beams using an external DC source, to assist emerging research fields which require 10–100 keV light ion beams. This makes an excellent, readily available facility which can be fully utilized at either keV energies for irradiation as described here, or MeV energy for ion beam analysis.

2. External DC source setup

Our accelerator is a model AN-2500 VDG manufactured in 1980 by High Voltage Engineering Corporation. It uses an RF ion source to provide positive ions which are accelerated up to 2.5 MeV in energy. However, to obtain and maintain a stable beam of ~100 keV or less with an unmodified VDG is extremely difficult, as it was never designed to produce ion beams at such low energies. The main factors affecting beam stability are the terminal voltage ripple due to the belt charging system, and the voltage stabilization using corona discharge feedback. New generation polymer belts developed in recent years have provided improved beam stability characteristics over traditional belt types with reduced terminal ripple effect. The major problem then, at such low beam energies, is the reduction of the corona discharge current to negligible levels even at the maximum extension of the corona assembly, resulting in the failure of the corona stabilization system. Overcoming this problem would involve modification to the existing corona assembly, which is a non-trivial process and may also affect the operation of the VDG at high voltages. Here we present a relatively simpler setup where we bypass the belt charging and corona stabilization mechanism to provide an external source of stabilized high voltage to the terminal.

Fig. 1 shows the schematic setup of a standard VDG system attached with an external stabilized DC source (Glassman WR100), capable of supplying a maximum voltage of 100 kV with $\leqslant$0.05% voltage ripple. The accelerator tank was removed for the positive HV attachment to be made directly to the terminal, and the external source shares the same ground as the accelerator. The VDG was operated under open atmosphere, which is not a serious concern for sub-100 kV terminal voltages, so long as suitable safety precautions are taken. The in-built corona beam stabilization was not

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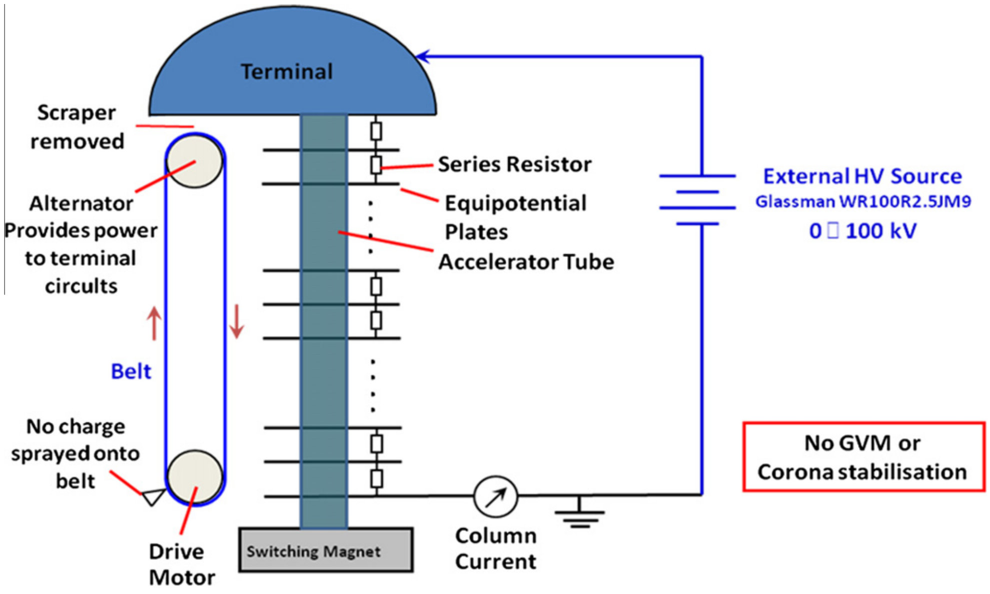

Fig. 1. Schematic of the Van De Graaff machine connected to an external DC source.

used, since the voltage stability is already provided by the external source itself.

Though the belt was no longer used to charge the terminal, it still had to be driven by the drive motor in order to turn the alternator which powers the internal circuits within the accelerator, including the ion source. To reduce the interference of the turning belt to the terminal voltage, no charge is transferred to the belt, and the scraper brush between the belt and terminal was removed. Under such an arrangement, it was possible to obtain a stable 50 keV H_2^+ collimated beams of up to 150 nA within a circular beam spot of ~1 cm diameter on target, which translates to a current density of ~190 nA/cm^2. This allows the irradiation of 1 × 1 cm^2 samples with a fluence of 10^{15} ions/cm^2 in about 20 min.

3. Low energy irradiations of silicon

Ion irradiation may be used for nanostructure fabrication on Si, where the irradiation significantly increases the resistivity of Si near the end of ion range [14]. Subsequent electrochemical etching with dilute hydrofluoric acid (HF) results in a reduced hole current and hence a reduced porous Si (p-Si) formation rate. High aspect ratio Si nanostructures with pre-determined shapes can therefore be formed by either direct write with focused ion beams, or by selective broad beam irradiation with use of patterned polymer masks [14]. MeV ion beams have been used to make structures many microns thick. We are moving towards lower energies (i.e. sub-100 keV ion beams) to make thinner Si structures and to reduce feature dimensions. Here, we demonstrate the use of ion irradiation at energies 35–50 keV using our external DC source setup for microfabrication on Si.

Test structures were first fabricated in medium resistivity (0.2 Ω cm) p-type Si wafer which was covered with a 2000 mesh Ni grid with period of 12.7 μm and thickness of 2 μm. It was then irradiated with a broad beam of 50 keV H_2^+ molecular beam, which has a projected range of ~280 nm in Si as calculated by SRIM [15]. The sample was irradiated to a fluence of 10^{15}/cm^2, and subsequently etched with 24 vol.% HF at a current density of 40 mA/cm^2 for 1 min, forming a p-Si layer of ~2 μm in thickness around irradiated regions, which remained as bulk Si since current does not flow through it. The p-Si was then removed with dilute potassium hydroxide (KOH) solution, leaving behind the Si nanostructures.

Fig. 2(a) shows a Secondary Electron Microscope (SEM) image of the top view of the as-etched sample prior to KOH removal of p-Si. The lighter-colored irradiated regions of 5 × 5 μm square holes are clearly seen in contrast to the darker, un-irradiated p-Si regions. Fig. 2(b) shows the cross-section SEM image of an irradiated square grid, also with p-Si still intact. The irradiated region is ~310 nm in thickness, in good agreement with the value obtain from SRIM for the ion range. The Si supporting pillar underneath shows significant undercut, demonstrating the flow of the hole current beneath the irradiated region during HF etching. After KOH removal, Fig. 2(c) and (d) shows the array of free-standing irradiated grid structures with their pillar supports. The surface of the square plateau on top of each pillar is not flat, but has a crater-like depression at its center. This has not been previously observed in this mode of silicon micromachining and is probably due to the continued flow of hole current during etching from the bulk Si pillar support directly through the irradiated plateau, forming p-Si on the top, resulting in the craters after removal of p-Si. Such direct flow of current is possible for thin irradiated layers of a few hundred nanometers created by sub-100 keV ion energies and low ion fluences.

Smaller structures may be fabricated by using polymer resists patterned using an electron beam lithography, which allows for structures with nanometer dimensions and of arbitrary shapes. Here we demonstrate a simple case where lines and dots are irradiated using this method. A layer of poly(methylmethacrylate) (PMMA) positive resist was spin coated onto the same Si wafers as above, and patterned using a focused electron beam. These were then developed, removing the patterned regions exposed to the e-beam. SRIM calculations indicate the respective projected range of the ions at ~400 and ~500 nm within PMMA, and the thickness of the PMMA layer of each sample was designed to be of the same order of magnitude. Subsequently, the samples were irradiated separately with beams of molecular H_2^+ ions at energies of 35 and 50 keV, equivalent to protons at 17.5 and 25 keV, respectively. After irradiation, the patterned PMMA layers were removed, and the samples were electrochemically etched.

Fig. 3 shows an optical micrograph of the resultant p-Si surface. Fig. 3(a) shows lines irradiated using 35 keV H_2^+ beam at a fluence of 10^{14}/cm^2. The exposed line patterns in the PMMA are 70 nm in width and separated by gaps of 2 μm, while the resulting Si lines remaining after irradiation and etching are about 200 nm in width (as determined by cross-section SEM). The increase is due to both a

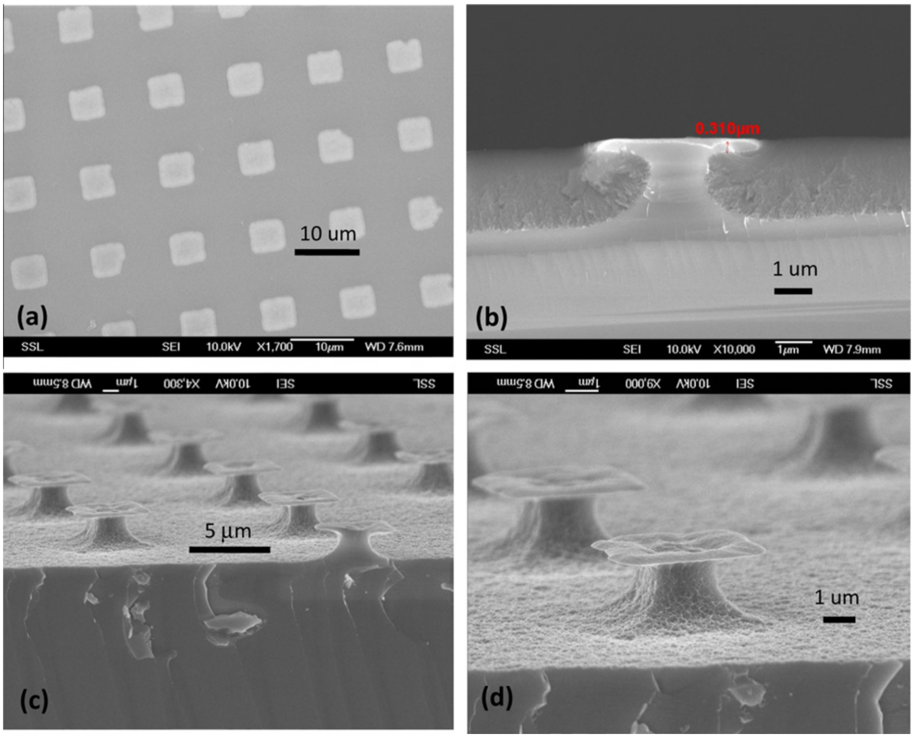

Fig. 2. SEM images of: (a) top view of irradiated regions with p-Si intact, (b) cross-section of a grid structure with p-Si intact, (c) and (d) arrays of free-standing nanostructures after KOH removal of p-Si.

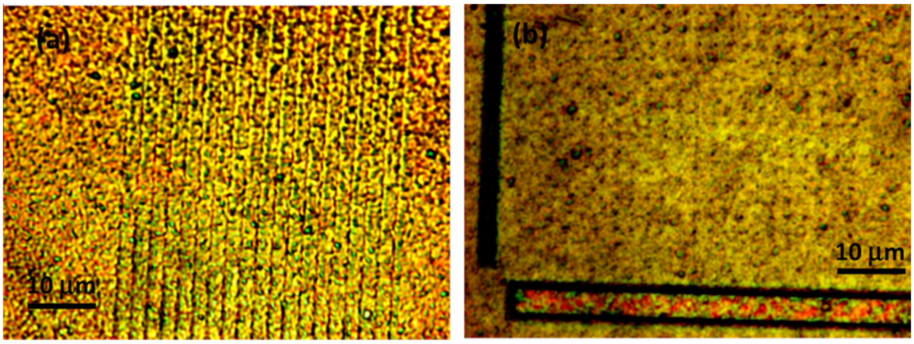

Fig. 3. Optical micrographs of different irradiated shapes using PMMA masked patterned by e-beam lithography after dilute HF etching: (a) shows irradiated lines using a 35 keV H_2^+ beam at fluence of $10^{14}/cm^2$, (b) shows array of dots with side markers using a 50 keV H_2^+ beam at fluence of $10^{14}/cm^2$.

broadening of the ion distribution within Si at the end-of-range, and the deflection effects of the hole current away from the irradiated volume [14]. Fig. 3(b) shows an array of dots written using holes of diameter ~100 nm on PMMA with two broad location markers. These results demonstrate the versatility of this method, small high aspect ratio nanostructures of any shape may be created. The use of medium energy ion beams in conjunction with thin polymer resists allows feature sizes of a few hundred nanometers to be produced, compared with the use of MeV ions where the greater lateral beam spreading has limited feature sizes to about 2 µm [14].

4. Conclusions

We have described the setup and the production of sub-100 keV ion beams using an external DC source connected to an old VDG accelerator. To demonstrate the use of ion beams produced in this manner, medium energy H_2^+ beams were used to fabricate arrays of microstructures on Si with dimensions down to 200 nm. This setup demonstrates new applications and research areas for VDG accelerators.

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