Mechano-magnetic and ion-beam influence on Si-based films for memory and switching devices

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ABSTRACT

Thin films deposited on silicon are the building blocks of memory devices starting from memristors to MRAM. The phenomena occurring on the surface and interface can be influenced by external stimuli like temperature, pressure, ion beam irradiation, etc. A study focusing on the different aspects like hysteresis and defect-generated conducting paths along with super Para magnetism and exchange bias have been done on Si and films deposited on Si for memory devices. Th ion irradiation on Si showed energy recoils and related phenomena useful for the fabrication of memristor devices.

Keywords: Memory and switching devices, thin films, mechano-magnetic, ion-beam

I. INTRODUCTION

Memory devices are mostly based on surface modification of silicon which can be either in the form of thin-film deposition and/or ion beam irradiation. Memristive devices are emerging these days which are used in neuromorphic computing and are based on thin films of Transition metal oxides compatible with CMOS. Going to lower dimensions 0D, 1D, and 2D lead to advances in the nanoelectronic phenomena, and mimicking a biological neuron becomes more prominent based on Van der Waal's heterojunction-based bio-inspired devices using Artificial Neural Network (ANN). MoS_2-based memtransistor and CNT are useful neuromorphic systems used in biosensing. The voltage dependence resistance of memristors is sometimes associated with the different phases in the material. Memristors based on Si nanocrystallites in SiO_2 matrix by sputtering which is compatible with CMOS and joule heating gets minimized [1-8].

Thin films memristor from hBN and SiC show good binary resistive memory switching which is beneficial for memory devices. Silicon-based piezoelectric nano/micro electromechanical systems (N/MEMS) are being integrated with memristors. The nano resistive switch properties can be studied with the help of nanoindentation as reported for amorphous (a-SrTiO3) perovskites memristors [9].

II. EXPERIMENTAL

Thin films of SiCN and multilayered magnetic films of Co and Co/CoO were deposited on Si substrates by magnetron sputtering. A sintered SiC pellet was used as the target and Nitrogen gas along with Argon was introduced in the evacuated chamber for SiCN deposition on Silicon, details which have been published previously[10]. Nanoindentation was done on the SiCN films by MTS (USA) nanoindenter. The mechanism of nanoindentation is given in details in ref [11, 12]. The Co and Co/CoO/Si films were irradiated with Si and Ar ions at Inter University Accelerator Centre, New Delhi, and their surface morphology, as well as magnetic studies, were performed[13].

III. RESULTS AND DISCUSSIONS

Nanoindentation has also been used in for magnetoelectric memory devices [14-17]. Recent studies have also shown the influence of electric field on nanoindentation with an increase in maximum indentation depth and final penetration depth with an increasing electric field. The influence is due to competition between mechanical load and electric field in the domain switching process [18]. The fracture studies of materials used in Li batteries have been done through nanoindentation. Recent studies have also shown an effect of charge states on the yield and elastic modulus obtained through stress-strain plots based on nanoindentation using the power-law hardening model for Li_xSn alloys [19]

Current can pass through the contact region of the conducting indenter and surface. The resistivity offered to the current as a result varies with the forces applied causing plastic deformation. Plastic deformation has been a major contribution to resistivity which is very well established as the dislocation can as scattering centers for the electrons. The resistance of the contact region mentioned above has two contributions viz. $R = R_c + R_f$, where R_c is the constriction resistance which depends on Bulk properties and R_f is the contact resistance due to the property of the surface layer [20]. If the shape of the contact region is considered as a circle of radius a, the $R_c = \frac{\rho_{1}` + \rho_{2}`}{2a}$ where $\rho_{1}`$ is the resistivity due to tip and $\rho_{2}`$ is for the sample. For a circular region $R_c = \frac{\rho_{1}` + \rho_{2}`}{2}\sqrt{\frac{\pi H}{F}}$ where H is the hardness and F is the force applied [21]. For the Berkovich indenter, the contact region is no longer circular and we take 24.5 h^2 as the contact area which modifies the resistance equation as $R_c = \frac{\rho_{1}` + \rho_{2}`}{2h}\sqrt{\frac{\pi}{24.5}} = 0.18\frac{\rho_{1}` + \rho_{2}`}{h}$. The fractured region or the heavily plastically deformed regions should also influence the electrical properties as they indicate high strain fields surrounding the indentations which should interfere with the free electron flow motion. The force during nanoindentation and the current passing in the contact region vary with time [21]. A higher value of impulse is causing a lower current value hence a higher rate of force application causes an increased dislocation jamming causing a higher scattering of the conducting electrons.. The importance pf impulse in nanoindentation has been reported.[22]

Piezoresistive MEMS used in pacemakers is based on impulse received from the heart's vibration for energy production proving a longer lifetime of the device. A silicon-based MEMS cantilever is used which uses CMOS compatible AlN as the piezoelectric layer and works on shock-induced vibration producing energy. SiCN having piezoelectric property can replace AlN [23] The mechanical response of N/MEMs under impulse loading is a major criterion for device fabrication [24]. Cantilever-based MEMS resonator sensors suffer the problem of un attainment of homogenous mass sensitivity. The intensity of vibration being highest at the free end of the cantilever makes the mass sensitivity highest and reduced as one move towards the fixed end. The resonant frequency of operation is inversely proportional to the mass., impulse plays a very significant role in these devices. Nanoindentation and stress analysis on cantilever nanobeams have been performed and reported [25].

A. FM/AFM FILMS

A correlation between nanomechanical and magnetic properties can be the basis of futuristic memory devices. Co/CoO films on Si substrates have shown increased hysteresis and exchange bias on lowering of temperature. This FM/AFM undergoes pinning of magnetic diploes at the interface which causes a shift in the M-H plot; Si ion-beam induced dewetting and Ar ion-induced super-paramagnetism have also been observed. This superparamagnetic effect observed in the case of Co/Si is the basis of futuristic memory devices [13].

Nanoindentation on soft magnetostrictive FeCoCr films for magnetic-microelectromechanical (MagMEMs) applications [26]. The speed limit of today's memory and switching devices is 1 ns/bit. Although patterned cobalt films have been fabricated for device performance, the magnetization is somewhat nondeterministic at this level [27]. These FM/AFM structures fabricated on SiO_2/Si as shown in **Fig 1 (a)** if made into use will cause patterned exchange bias and superparamagnetism increasing the magnetic storage and faster Switching (~ ps/ bit). A mechanism for the fabrication is given in **Fig 1(b)**.

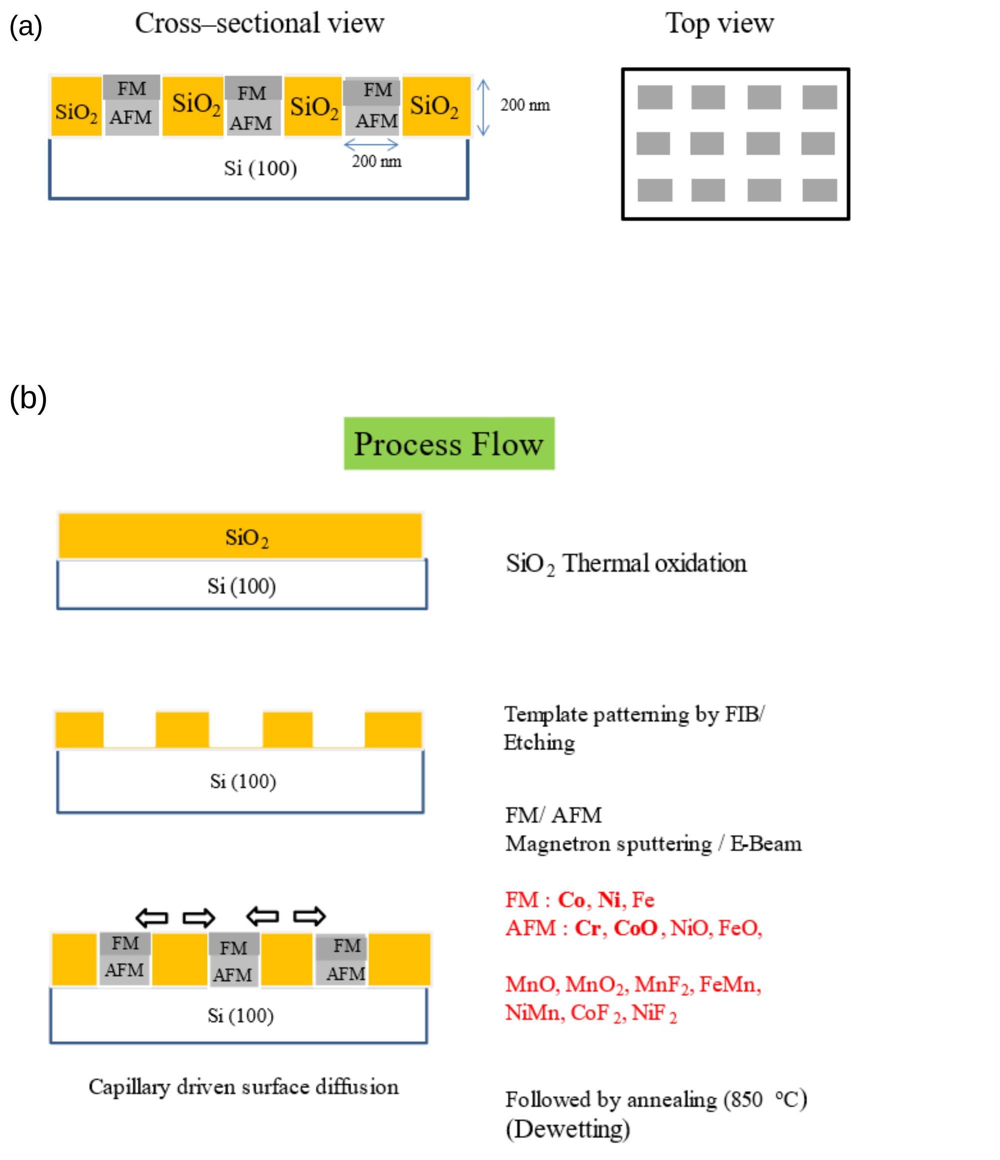
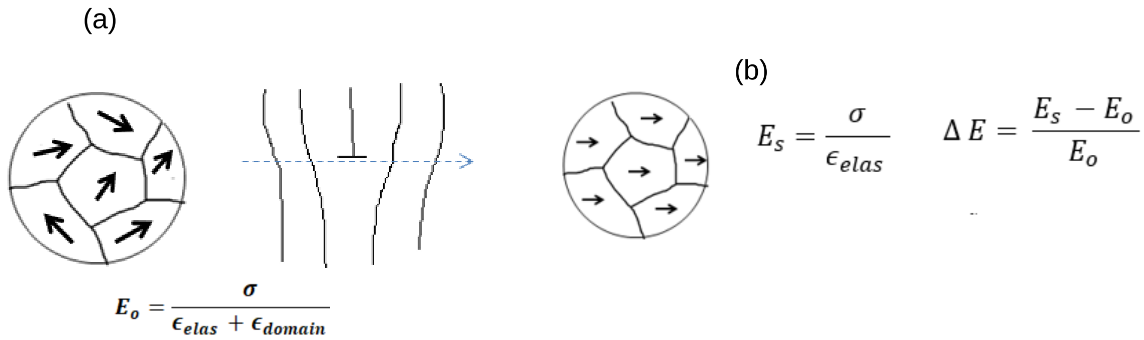


FIG. 1. a) Patterned FM/AFM systems b) the fabrication process

There also exists a correlation between mechanical and magnetic properties at nano dimensions. A strain gradient-induced domain wall rotation is observed in ferromagnetic thins films (Co, Ni, Fe) mainly deposited on Si substrates known as the flexomagnetic effect. This arises since dislocations require extra energy to pass through magnetic domain walls. However, in the saturated magnetic field as most domain walls vanish, the dislocation mobility increases which increases the elastic modulus (E) whereas decreases the hardness (H) as it is the resistance towards dislocation motion (**Fig 2**) [27].



$$E_o = \frac{\sigma}{\epsilon_{elas} + \epsilon_{domain}}$$

$$E_s = \frac{\sigma}{\epsilon_{elas}} \qquad \Delta E = \frac{E_s - E_o}{E_o}$$

FIG. 2. a) dislocation motion hampered due to domain wall b) Saturation magnetization causing an increase in elastic modulus

B. *Ion beam implantation on Si*

Ion beam implantation on Si has been done previously to change the morphology and make it applicable for device fabrication especially micro sensors [29 – 34]. Ion beam-assisted solid phase epitaxy of SiGe and its application for analog memristors have also been reported recently [35]. A simulation-based study of Na+ ion implantation on Si was carried out using SRIM/TRIM software[36]. The simulated plots showing range distribution and recoil ionization are given in **Fig 3**. These factors affect the morphological changes useful for CMOS-compatible wafer-scale fabrication of memory architectures based on memristive devices [37]. These energy recoils produce defects and amorphous pockets and may also lead to recrystallization which may turn into conducting paths useful for device fabrication. The radiation-induced vacancies influence the device operation by changing the current-voltage characteristic and state retention ability of memristors.[38, 39]

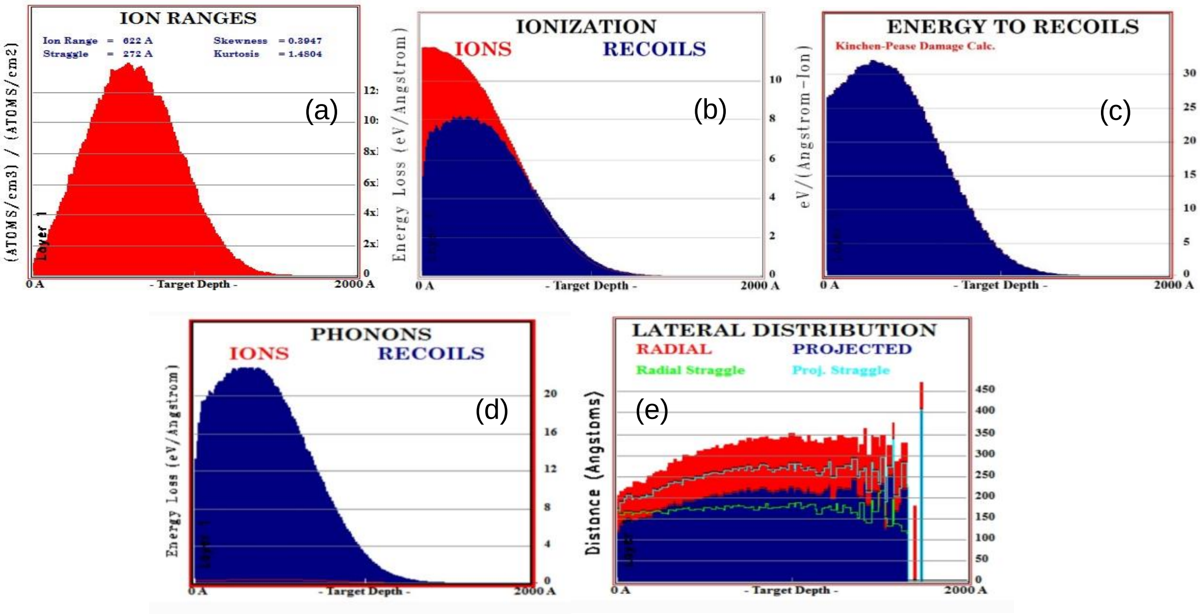


FIG. 3. a) Ion range distribution and b) Ion and recoil ionization c) Energy to recoil d) loss of energy to phonon recoils and e) Lateral distribution curve for Na ion on Si.

IV. CONCLUSIONS

Silicon as a substrate for thin film deposition to make memory and switch devices have been investigated. The use of nanoindentation for the use of silicon-based thin films in micro-electro-mechanical devices was shown. Patterned FM/AFM structures with ion beam radiation were discussed providing higher memory storage and faster switching, Simulation studies on ion beam irradiation on Si were done supporting the cause.

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CONFLICT OF INTEREST

The authors have no conflicts to disclose

AUTHOR'S CONTRIBUTION

Arnab Sankar Bhattacharyya was involved in writing and framing the ideas of the manuscript and doing the experimental work.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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