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Application of Corona Charge Deposition Technique in Thin Film Industry

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Abstract

With the advent of new materials, microchip industry is investigating new architecture to further scale down the device size. New technologies are on the way to achieving this goal without compromising with the device's performance and benefits. In this new scenario, corona charge deposition technique (CCDT) has become an indispensable part of the thin film industry. Due to the non-invasive and non-destructive nature of corona charge ions, they are effectively being used to improve the device properties. They are also useful to understand the electrical properties of insulators and other materials. Corona-Kelvin non-contact metrology or the C-KM is the most recent development in this field. In this review, the applications of corona charge deposition technique in the semiconductor industry have been reviewed. Further, the methodology involved is described. The advances as well as challenges and improvements including the future research are also discussed.

Keywords

Corona Charge, Microchip Technology, Thin Film, Corona Grown Oxide

1. Introduction

The scaling down of the microchip has somewhat reached to its limits [1]. New technology [2] [3], new materials [4] [5] and new architecture [6] [7] [8] are under investigation for the same or better performance benefits. The thermally grown SiO_2 is not the only dielectric in use for device fabrication. The thermal budget has brought many other dielectrics, high-k as well as low-k dielectrics and advanced material in the forefront. This has partially replaced the SiO_2, high-k dielectric for front-end of-line fabrication (FEOL) and low-k dielectrics for back-end-of-line applications (BEOL) [9]. Even silicon is not the only device material and is now has to be replaced by silicon on insulator (SOI) [10] [11], strained silicon, Si Ge [12] [13], SiC, and GaN [14] [15] [16]. Different depositions and surface passivation techniques are either in use or under investigation to meet the requirements and improve device performance [13] [17] [18]. Non-contact metrology is standardized and in use for industrial application although improvements are required in this field [19] [20] [21] [22].

In the present context, corona charge deposition technique has emerged as a novel tool in the thin film industry. Due to the non-invasive and non-destructive nature of corona charge ions [23], it is the most widely used deposition technique to check for defects at the Si/SiO_2 surface [24]. The sample can be discarded at an early stage of processing if needed, making the device fabrication process cost-effective. The ease of application of corona charge ions at room temperature has proved it to be more reliable than other higher temperature processes. The wide range of applications includes analysis and improvement of device properties [24] [25] [26] [27], understanding the electrical properties of insulators and other materials [25] [26] [27] [28], failure analysis of ICs [29] and non-contact metrology [19] [20] [21] [22].

In this paper, the status of all these fields of application of corona charge deposition is reviewed. The advances, challenges and improvements associated with the application of this technique have also been discussed.

2. Study of SiO_2 Film and Oxidation under Corona Discharge

During the early 70's, efforts of the RCA laboratory initially employed corona discharge in air to study the electric breakdown field of thermally grown SiO_2 films [25]. The procedure was non-contact and non-destructive. Corona charge was applied on bare Si/SiO_2 surfaces, eliminating the need of a metal electrode, thus making it completely different from the conventional approach. The conventional approach used metal-oxide-semiconductor (MOS) capacitors to measure the electrical parameters of the Si/SiO_2 surface.

One study reported that the corona discharge set-up that was employed, was a point to plane corona discharge system [23]. This was mostly in use for laboratory investigations. It is limited to mapping of a small region of the device surface. The external bias applied by corona ions causes bending of the bands in silicon and gives rise to a surface potential across the Si-SiO_2 surface. Kelvin Probe [28] was used to measure the surface potential, in which positive as well as negative corona discharge was employed. The results obtained with this set-up were remarkable as the steady value of electric field E with negative corona charging was found to be twice as large as it is for positive corona charging. The other remarkable feature of these experiments was that the field thus measured was independent of the conductivity type, and doping level of the silicon. The electric breakdown field of SiO_2 thus measured was found to be higher than what has been reported in other publications [25].

One study employed a negative point oxygen corona discharge to study the stress relaxation mechanism in SiO_2 films [26]. In this study, isotope tracer structures were used to study the corona induced relaxation mechanism. Apparently, the stress relaxation mechanism was the deciding factor in oxidant transport through the film.

Later, another study carried out whole wafer mapping of the SiO_2 film on silicon employing the corona charging technique [27]. The apparatus used in this study was like the one used in a photocopier. Negative air corona discharge was used in this paradigm. The maximum corona charge is limited by Fowler-Nordheim tunneling of electrons from the Si to the SiO_2 conduction band. The method was fast and gave whole wafer mapping in 10 - 20 minutes. Defect areas on the oxidized wafer could easily be located by corona charging as corona charge didn't get deposited on pinholes or defect areas.

The first review on uses of corona charge deposition technique in the semiconductor industry was published in late 1980s [24]. Applications of air corona charge deposition technique (CCDT) were used to understand the kinetics of oxide growth and physics of oxides. This article also proposed the usage of the methodology in device evaluation and failure analysis of high voltage devices. Failure analysis of junction field effect transistor (JFET) clearly established that a device is good by design, not because it is free from surface ions [29]. For these experiments, negative surface ion deposition from a dry air corona discharge was applied using a needle electrode and a control grid system.

One study reported that the corona discharge technique can be employed for oxidation of silicon [30]. A negative point to plane corona discharge in oxygen atmosphere at room temperature and above (25˚C - 500˚C) was employed to grow SiO_2 on Si wafers. As expected, the oxidation rate was a strong function of temperature. The oxide growth rate was much higher under corona discharge as compared to conventional thermal oxidation of silicon. The measured refractive index of corona grown oxide (CGO) for thick oxide was comparable to thermal oxide. The poor quality of CGO was revealed in another experiment by the research group, by the CV and IV characteristics of the MOS capacitors fabricated on this oxide [31]. For low temperature processing, this oxide can be selectively used.

Fourier Transform Infrared Spectroscopy (FTIR) analysis of silicon dioxide grown under negative corona discharge was reported by one study [32]. The results indicated properties of a fully relaxed silicon dioxide film with a contradictory nature. The results can be comprehensively explained only by assuming the presence of some mixed phase of SiO_2.

3. Improvement of Device Performance

Device quality improvement by deposition of corona charge ions is one of the precursors to explore and apply this technique. The study of transport of detrapped charges in thermal wet grown silicon dioxides electrets has been carried out employing this technique [33]. Electrets are dielectric material with quasi-permanent electric charge or molecular dipoles. They are located on the surface or the bulk of the dielectric. Therefore, electrets can store charges for a very long time as their decay time constant is much longer than the lifetime of the device, which has the dielectric [34] [35]. This property of electrets has made them suitable for applications in sensor technologies [36] [37], acoustic transducers [38] [39], micro relay switches [40], and dosimeters [41] [42]. Electrets can be organic or inorganic. Due to their compatibility with the silicon technology, inorganic electrets are of considerable importance in the field of micromechanics, and optoelectronics. The study of thermal silicon dioxide electrets formed by corona discharge and rapid thermal annealing suggests that electrets could be an effective means of improving the efficiency of Si based solar cells [17].

None-the-less, application of electrets films in micro devices is quite limited due to the limitations imposed by the corona discharge technique [43]. This technique necessitates those electrets films be formed on a flat surface of the base material. Injection of charged particles by ion implantation has the same limitation [44]. Electret films are hardly applicable to the side walls of very-high aspect-ratio trench structures that are widely used in modern MEMS devices. Techniques other than corona charge deposition and organic materials are being explored for this reason [45] [46].

Reducing surface recombination, also known as surface passivation, is of utmost importance for optoelectronic devices, especially solar cells. The interfaces and surfaces consist mainly of dangling bonds due to the abrupt discontinuity in lattice structure. These surface dangling bonds play a key role in unwanted surface recombination of photo generated electron-hole pairs. Different materials, methods and metrics are in use for surface and interface passivation including corona charge deposition technique. The technique has been explored for long term stability of the cells also. Recent reviews on solar cell technology discuss the developments in the last 20 years [47] [48]. The study chronologically discusses the materials, deposition methods, different dielectrics, and dielectric surface passivation methods along with the manufacturing details for silicon solar cells. The review presented by the authors [47] [49] reveals that c-Si based technology still dominates the solar cell industry. It is also well understood that among all the dielectric materials, surface passivation by SiO_2 is the most compatible with c-Si for solar cell applications. Additional surface passivation by corona charge deposition has been explored to further increase the efficiency of the solar cells [13] [48].

To the author's knowledge, first experimental investigation of field effect passivation of the Si-SiO_2 interface of thermal oxide by negative as well as positive corona charges was carried out on the oxides of solar cells and lifetime test structures in 1999 [50]. The extended SRH (Shockley-Read-Hall) formalism [51] was used to account for energy dependent capture cross sections over the band gap for a continuum of defect states present at the Si-SiO_2 interface. The influence of injection level, doping concentration and oxide charge was predicted and experimentally analyzed. For solar cells as well as lifetime test structures, a dramatic influence was observed on the surface recombination velocity (S_{eff}) at the Si-SiO_2 interface. Though the previously predicted extremely low values or S_{eff} well below 1 cm/s was not achieved experimentally, it was possible to reduce S_{eff} with high negative and even more with high positive charge densities. The results of the experiments on solar cell correlate well with the ones obtained on lifetime structures.

Recent study [52] shows that very large improvements in the passivation properties of films can be achieved by modifying their charge density. The detailed study of the long-term stability of the surface passivation and comparison with other techniques presented by other reports establishes the superiority of the corona passivation technique [13] [52]. However, the stability of the experimental solar cell structure needs to be extended to the practical life span of a solar cell before it can be used in industry.

Another study investigates the corona charged Si-SiO_2 interface under different operating conditions [53]. For corona charged SiO_2 the passivation quality was also investigated. An improved lifetime was observed above room temperature implying that the passivation quality improves above room temperature for corona charged SiO_2. However, at temperature greater than 50˚C, a degradation of the surface passivation was observed [53] [54]. Since solar cells operate at high temperatures, the technology needs further improvement.

4. Non-Contact Metrology

Non-contact metrology is the new trend in the semiconductor industry with the advent of newer materials and dielectrics, e.g., SOI (silicon on insulator), strained Si, SiGe, high k-dielectrics like Ta_2O_3, HfO_2, Al_2O_3, a-silicon (amorphous silicon), Photo CVD SiO_2 etc., and the fabrication processes. With the gradual transition of the industry from 130 nm to 65 nm and below [55] the FEOL features have reached atomic dimensions. Monitoring electrical properties of dielectrics with corona-Kelvin non-contact metrology is the standard practice in industry due to the ease of application as well as their non-invasive and non-destructive nature.

Modifications are in place for high-k dielectrics as well. Non-contact metrology helps making measurements of device properties possible at an early stage of fabrication. It has replaced or complement the traditional C-V (Capacitance-Voltage) and I-V (Current-voltage) measurements on MOS (metal oxide semiconductor) capacitors basically designed for Si based technology [18] [19] [20] [21]. In general, the metrology involves three elements, 1) Air corona discharge is used to place a precise amount of electric charge on a dielectric surface, 2) The surface voltage is monitored with the help of a vibrating Kelvin Probe and, 3) The semiconductor surface barrier potential, Vs, separate from the dielectric potential is determined/ measured. For oxides on SiC [56] [57], this metrology has been applied to the determination of the capacitance-voltage dependence, and Fowler-Nordheim characteristics of as grown dielectrics [58]. Tunneling due to substrate emission in oxide films on silicon can be accomplished by biasing the structures; with deposited corona ions and measuring the resulting potential decay with a Kelvin probe [59] [60]. The device reliability studies reported accumulation of positive charge in the oxide at a field higher than 11 MV/cm [59]. The Corona-Kelvin or C-KM metrology has been used for characterization of plasma nitrided SiO_2 also [19].

The first non-contact electrical measurement was performed in 1881 [28], and with more developments in the coming years [61]-[68]. Surface photo voltage (SPV) measurements for characterization of semiconductors was finally fully implemented by RCA in 1983 [69]. ASTM standards were developed for non-contact measurements of recombination lifetime and diffusion length [70] [71] [72] [73].

Measurements of device parameters can be divided into three main groups: the characterization of bulk substrate material, the near surface region, and the dielectric films [74]. The parameter associated with the bulk is minority carrier lifetime, diffusion length, and iron concentration (Fe). The most used techniques are photoconductance decay (PCD) and the SPV (Surface Photo Voltage) in commercially available metrology. SPV measurements are often associated with corona charging.

Typical parameters characterizing the near surface region are generation lifetime, near surface recombination lifetime and near surface doping. It is the near surface region properties which govern the device performance. Commercially available metrology employs the non-contact corona charging technique for the measurement of electrical doping profiling as well as the recombination lifetime [19] [20] [75].

Characterization of dielectrics and interfaces include equivalent oxide thickness (EOT), leakage current, total charge, flat band voltage, density of interface traps, soft breakdown field and mobile ion concentration. The two techniques mostly in use for this purpose are the Corona oxide semiconductor (COS) technique [75]; and the corona oxide characterization of semiconductor (COCOS) technique [21] [76]. As the name suggests, both the techniques carry on the deposition of corona charge on the dielectric surface to apply bias to the dielectric and the semiconductor. For high-k, ultrathin dielectrics non-contact C-V technique is based on a differential quasistatic C-V that is generated using time resolved metrology combining corona charging and contact potential difference (CPD) [22]. For ultra-thin dielectrics in the presence of substantial leakage current, steady state method has also been utilized [77]. Non-contact metrology had been reviewed in 2003 to discuss the advantages, define the problem areas and suggested improvements [74]. The questions and concern raised by the authors of this study after the experimental investigation of the metrology convey that it is not in a robust profile. They recommend additional efforts to make this promising metrology reliable and standardized in a better way.

The corona charging technique has been used in numerous electron spin resonance (ESR) experiments also by several groups to study the defects centers in Si/SiO_2 system. Low field corona biasing [78] [79] [80] [81] [82] as well as high field corona biasing [83] [84] has been used by different groups; and their results differ from each other. The corona charging technique has been termed "inherently unreliable", and invasive, when applied to thin oxides on silicon by one group. Their study shows that it modifies the inherent properties of the entity to such an extent that the study of ESR-active defects can be completely disrupted [85]. However, experimental study carried on low as well as high fields for both thick and thin oxide films establish the non-invasive nature of the corona charging technique [86]. The author argues that a distinction must be made between high and low field corona biasing. High or low fields biasing by corona charge are like high/ low field stressing via conventional gate electrode. A comparison between biasing with 7 MV/cm (high field) and 4 MV/cm (low field) for the same time period revealed that generation of defect centers takes place only when high field corona biasing is applied. High fields generate large densities of paramagnetic centers and are therefore damaging. Their findings are consistent with those reported by other authors [87] [88] [89] [90] [91]. Low fields don't generate defect center and are therefore safe to use [78] [79] [80] [81] [82]. The results are the same irrespective of the thickness of oxides. [86] However, these claims have been refuted in another study [87]. Defect generation at the $Si-SiO_2$ interface was observed at electric field as low as ~ ±1.2 MV/ cm establishing the corona charge biasing technique as fully invasive and non-reliable. The authors used (Capacitance-Voltage) CV technique and minority carrier lifetime measurements instead of ESR as the chief characterization tool.

5. Device Cooling with Corona Charge

The latest approach to electronics cooling is by employing a corona discharge. The idea was conceived in 2003 [92] and is in use at industrial level.

The new design replaces the mechanical fan used for heat dissipation in electronic devices by electric wind generated by corona discharge [92]. The next generation of electronic devices have "ionic wind" or "electric wind" to cool the device [92] [93]. The basic concept as discussed by the different research groups is to generate the ionic wind or electric wind between the two electrodes using corona discharge technique. One of the electrodes generates positively charged gaseous ions; and the other, the collector electrode attracts it. When these ions move through the air flow duct between the two electrodes, they collide with other air molecules. Momentum transfer takes place between them, and the air flow begins. The electronic system is situated in the air flow duct, towards which these electrons and air molecules are directed. At the end of the duct, they finally get collected by the collector electrode. Different aspects and experimental design of the new technology is being explored by different research groups [92] [93] [94].

6. Discussion

The wide range of applications has established the corona technique as the most promising technique in the semiconductor industry. DC positive as well as negative corona discharge systems are in practice for deposition of surface ions [24] [75]. Only unipolar space charge limited coronas are used. The primary reason of using such corona is the absence of free electrons or bipolar conduction coronas like streamers. The saturation current for unipolar coronas is given by Is $\cong 2\ \mu\varepsilon_0\ V^2/d$ for an applied voltage V and point to plane distance d [23]. At room temperature and pressure, DC positive corona discharge ions in dry air primarily consists of H_3O^+ ions and negative corona discharge comprises of CO_3^- ions. Corona ions thus generated have been reported as non-invasive and non-destructive [23]. The technique has been safely applied for detection of defects in oxides during device fabrication procedures as well as testing of the product, i.e., the failure analysis of IC's [24] [29].

Corona charge deposition technique is in practice to study the electrostatic properties of oxide as well [25] [26] [27] [75]. More convincing results have been obtained with this technique as compared to that with the conventional metal electrode [25] [26] [27]. The technique was successfully applied on oxidized samples to determine the oxide charge density (Q_o), interface trap density (D_{it}), and flat band voltage (V_{FB}). On junction devices, near surface doping density could be measured and with some modification's minority carrier lifetime could also be determined [75].

Corona ions deposition technique has been applied to study the defect centers in Si/SiO_2 surface in ESR (electron spin resonance) experiments [86]. However, the non-invasive nature of corona charge ions has been studied and challenged at the same time. Different groups involved in ESR studies of P_b centers employing this technique have frequently challenged this concept [87]. For MEMs devices also this technique appears to be the limiting factor. Further investigation is needed to successfully apply it to charge the electret films in MEMs devices [43]. The field of oxidation of silicon under corona discharge needs further investigation [30] [31] [32].

Silicon wafer solar cells are the leading photovoltaic cells changing the commercial market of electricity. All the three types of solar cells commercially available are based on silicon with a maximum efficiency reported between 20% - 26% [95] [96] [97]. III-V/c-Si tandem solar cells are also being investigated for better energy yield and an efficiency of >25% has been reported [98]. Corona charge deposition technique is under investigation for further improvement of the performance of the solar cells.

Corona charge deposition is widely used in commercial device reliability characterization. An extensive study to review the prospects of the metrology for ULSI technology has been carried out by one group [74]. The authors provide qualitative and quantitative estimates of the accuracy on the parameters that characterize the bulk material, near surface region and the dielectric/ interface region. In-depth study on lifetime and concentration of heavy metals as well as their diffusion length, doping concentration, generation lifetime and recombination lifetime of carriers, surface voltage, stress induced leakage current and interface trap density has been presented. An estimation of deviation of the parameters from their "true (mathematically calculated) values" reveals that the corona based non-contact electrical metrology needs to be improved and further standardization is required [74].

Corona discharge technique is all set to replace the mechanical fan by generating "ionic wind" for electronic device cooling. Different aspects of the design are under investigation [92] [93] [94].

7. Conclusions

In the present review, the many applications of the corona charge deposition technique in thin film industry have been presented. The important conclusions are as follows:

1) Corona charge deposition is a useful method of device characterization and testing in the semiconductor industry.

2) The technique is under investigation for improving the efficiency of Si based solar cells. The experimental results achieved so far at the laboratory level have been promising.

3) It is the latest technology in use with the Kelvin Probe for non-contact metrology. It is in use at the industry level. However, the in-depth study of the corona based non-contact metrology reveals the need of further improvement and standardization.

4) It is the newest technology for device cooling. Corona based "ionic wind" is the next generation cooling fan for electronic devices. Different aspects of the design and technology are under investigation.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Abbreviations

CCDT, Corona Charge Deposition Technique,
CGO, Corona Grown Oxide,
C-KM, Corona-Kelvin Metrology.