Diffraction Originated Local Heating of Nanometer Scale Device Patterns in Lamp-Based Rapid Thermal Annealing

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The process results on blanket Si and patterned Si wafers are often very different. Process variations in conventional lamp-based rapid thermal processing (RTP) systems due to pattern size, density and structure dependence under nearly identical process conditions are well known as the "pattern effect", but without identifying the root cause. As device dimensions shrink, pattern-induced variability of process results increases which significantly affects the process window, device yield and manufacturability. Understanding the underlying physical causes of the "pattern effect" is very important to systematically improve device performance, yields and manufacturability. In this paper, the impact of device pattern size and density on process variations in RTP steps was analyzed. According to the analysis, diffraction of light from the periodicity of the nanometer scale device features can result in significant local heating near the critical depths for junctions and contacts.

Introduction

The process results on blanket and patterned Si wafers processed under nearly identical process conditions in conventional lamp-based rapid thermal processing (RTP) systems are very different. (1-5) This is often referred to as "the pattern effect" without identifying the root cause. As device dimensions shrink, variability of process results increases and device manufacturing can be significantly affected. (2-5) Understanding the underlying physical causes is very important in order to improve device performance, yields and overall costs.

Strangely enough, the laws of physics for diffraction of light, responsible for the local heating of nanometer scale devices in a radiation heating environment, are already understood as they relate to some process applications and even used to advantage. In lithography, it has long been recognized that, as the feature size of patterns approach the wavelength of the illuminating light source, optical resolution is compromised and diffraction effects must be considered in creating the masks to generate the desired patterns on wafers. (6-8) Lithography has recognized that the light sources are photon radiation sources and the wave characteristics of light must be considered. This insight has been ignored by the RTP community.

In this paper, the impact of device pattern size and density on process variations in rapid thermal processing was analyzed based on light interference with the periodic features of nanometer scale devices. According to the analysis, diffraction of light from the periodicity of the nanometer scale device features can result in significant local heating at depths critical for junctions and contacts. For nanometer scale devices, localized heating from the diffracted light becomes a significant factor and source of process variations.

Diffraction from Patterned Wafers

The patterned wafer is a collection of repeated patterns with diffraction grating-like characteristics. This was proved by irradiating a patterned wafer with a laser beam (visible spectrum) and observing the clear and brilliant two dimensional diffraction pattern (Fig.1). Light from the incident direction is diffracted by the nanometer scale patterns according to the specific wavelength and periodicity involved. Similar diffraction of light can be observed with a transmission grating (Fig. 2).

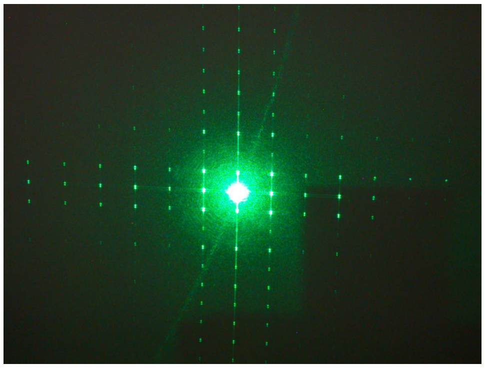

Figure 1. A typical diffraction pattern from a device wafer under laser beam irradiation perpendicular to the wafer surface.

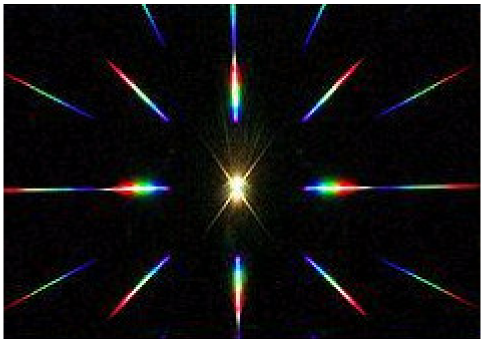

Figure 2. A white light source observed through a crossed transmission diffraction grating with a groove density of 530 lines/mm.

Diffraction angles from a transmission or reflection grating can easily be calculated. Wafers with periodic device patterns, on the order of the wavelength of the radiation illuminating them, can be treated as diffraction gratings to simulate the interaction between the photon energy and the on-wafer patterns. Figure 3 shows schematic illustrations of multiple order reflection and transmission diffraction from a transmission diffraction grating (or patterned wafer) under normal incidence of light beam.

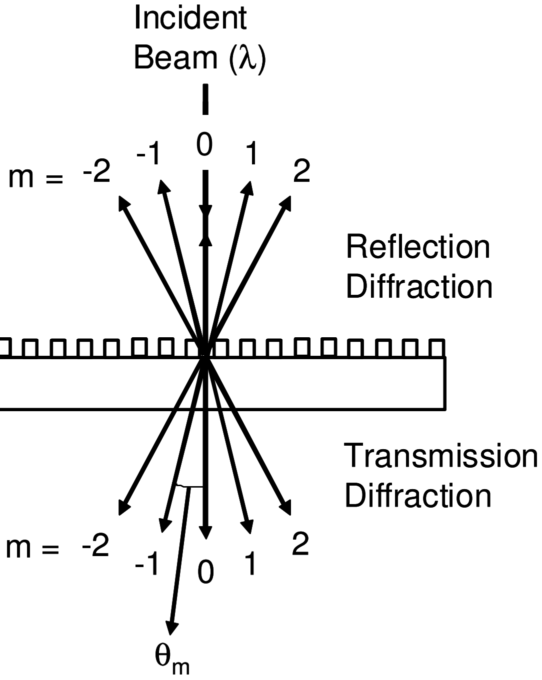

Figure 3. Schematic illustration of multiple order light diffraction from a transmission grating under a normal incident of light.

In the case of normally incident light on a patterned wafer, the diffraction angle of the m^{th} order diffracted beam in [°] is given as

$$\theta_m = \sin^{-1}\left(\frac{m\lambda}{d}\right)[°] \qquad [1]$$

where d is the periodicity of repeated patterns in µm and λ is wavelength of incident light in µm. In practice, a wide range of photon wavelengths irradiate patterned wafers at various angles of incidence.

It is quite complicated to model practical lamp-based RTP systems because of uncertainties in the process variables and interactions between variables. For simplicity, the first order reflection and transmission diffraction angles from a patterned wafer with pattern periodicity range of 0.4 µm ~1.3 µm (400 nm ~ 1300 nm) under normal incidence of white visible light (0.4 µm~ 0.7 µm) beam were plotted in Fig. 4 as a function of pattern periodicity and wavelength. As seen in Fig. 4, the first order diffraction angle becomes 90^o when the pattern periodicity is equal to the wavelength of normal incident light. The diffraction angle is equal to 30^o when the pattern periodicity is equal to two times of the wavelength of the normally incident light beam. As pattern size decreases, the diffraction angle becomes larger. Increase of diffraction originated local heating (for example, side wall heating of small size patterns) is expected in small size patterned. The degree of diffraction originated local heating can vary significantly depending on the distributions of pattern sizes and photon energies.

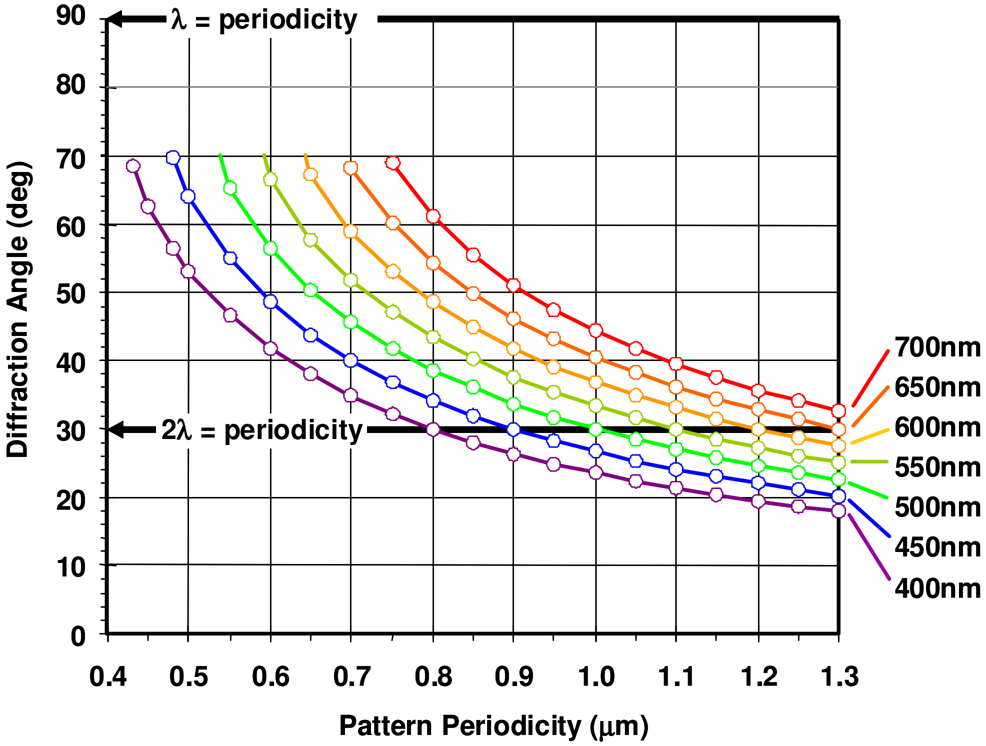

Figure 4. First order reflection and transmission diffraction angles from a patterned wafer as a function of pattern periodicity and wavelength.

Analysis of Light Diffraction in Patterned Wafers

The implication of diffraction on patterned wafers was estimated by considering the periodicity of patterns and incident photon energy distributions. Here, a simple array of Si islands (300 nm x 300 nm) surrounded by narrow (<800 nm) STI (shallow trench isolation) undergoing thermal processing was considered.

As the wavelength of incident light becomes longer, the angle of diffraction increases for a given pattern periodicity. The first order diffraction becomes 90^o when the pattern periodicity is equal to the wavelength of the incident light. In other words, the first order diffracted beam cannot pass through the pattern. With wavelength shorter than the periodicity of patterns, the light diffracts as it pass the patterned structures. If the wavelength of the incident light is shorter than the pattern spacing, the first order diffracted light may hit the side walls of the patterns and become a localized, non-uniform and unintended heat source. When feature spacing is between 400 nm and 1400 nm, the first order diffracted visible light (400 nm ~ 700 nm) can be diffracted from 90° ~30° and becomes a significant localized heat source. As multiple feature sizes coexist in the same wafer, a large variation of diffraction angles is expected. Localized heating is expected in patterned wafers even under uniform irradiation of light.

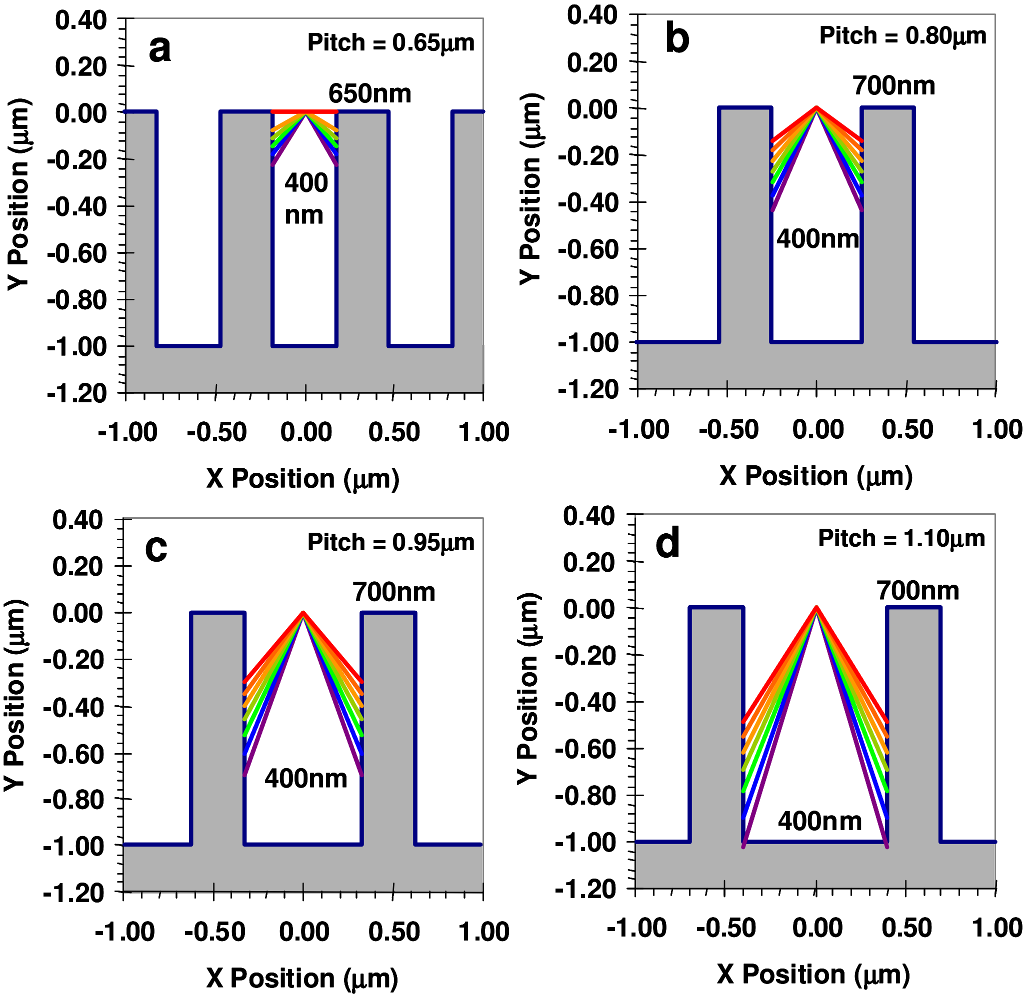

Figure 5. Schematic illustration of diffraction of normally incident visible light on periodic patterns of various pitch.

As we consider the STI-Si island example, the first order diffracted beam of visible wavelength region (400 nm ~ 700 nm) was traced as a function of slit spacing in Fig. 5 (a) ~ (d). For simplicity, the island size of 300 nm x 300 nm was fixed and only STI width was varied to demonstrate the impact of repeated feature size on the destination of the first order diffracted light. From the figure we see that the diffracted light will be absorbed by the Si side walls. The shorter wavelengths light have higher absorption coefficients in Si and contribute measurably to sub-surface local heating. As pattern periodicity becomes narrower, the diffraction angle becomes larger. When the pattern periodicity is twice as large as the wavelength of light, the diffraction angle is 30^o. As the pattern periodicity gets down to $1/\sqrt{2}\lambda$ and $2/\sqrt{3}\lambda$, the diffraction angle increases to 45^o and 60^o. Significant diffraction occurs as the wavelength is smaller than twice the pattern periodicity. At a spacing of 650 nm (active Si island width of 300 nm and STI width of 350 nm) in Fig. 5 (a), only light with wavelength shorter than 650 nm can be diffracted by less than 90^o. The sidewall heating by diffracted short wavelength light becomes significant in devices of small dimension. This side wall heating can result in critical dimension (CD) change and impact junction leakage in very small, nanometer scale devices.

Discussions

In the past, because the process window of thermal process steps for micron to submicron scale devices was wide enough, and optical interference between the light and devices for this scale was quite small, these process non-uniformities were unknowingly tolerated. As feature sizes decrease, optical interaction increases and allowable processing variations shrink rapidly if we are to maintain wafer level, chip level and die level process uniformity and repeatability. Small process variation often results in fatal device failures. It is time to carefully evaluate all potential sources of variations, including the effect of light diffraction by small features on wafers.

To reduce the impact of light diffraction, one should move away from the short wavelengths as a heat source in radiation heating. If the IR frequencies are used as a heat source, the feature size and wavelength no longer couple as efficiently. Furthermore, more uniform heating in the depth direction can be achieved due to the small light absorption coefficient at longer wavelengths.

A practical example of such RTP results was observed on Ni-silicided small islands with various shallow trench isolation (STI) widths. The experimental work is fully described in the paper by Itokawa, et al. (9) In this work, a range of silicon island and STI configurations undergo a NiSix process in which two different approaches to silicide formation are used. One utilizes tungsten halogen lamp radiation for Ni silicide formation while the other uses an isothermal hot-wall process chamber, minimizing radiation heating. The findings concluded that junction leakage is greatest in small island configurations using radiation based RTP, which undergoes significant diffraction, resulting in non-uniform heating and loss of critical dimension control. The non-radiation based isothermal chamber minimized radiation in the thermal process and minimized junction leakage. The results are shown in Fig.6. The explanation of this phenomenon is rooted in the diffraction analysis in the discussion of Fig. 5.

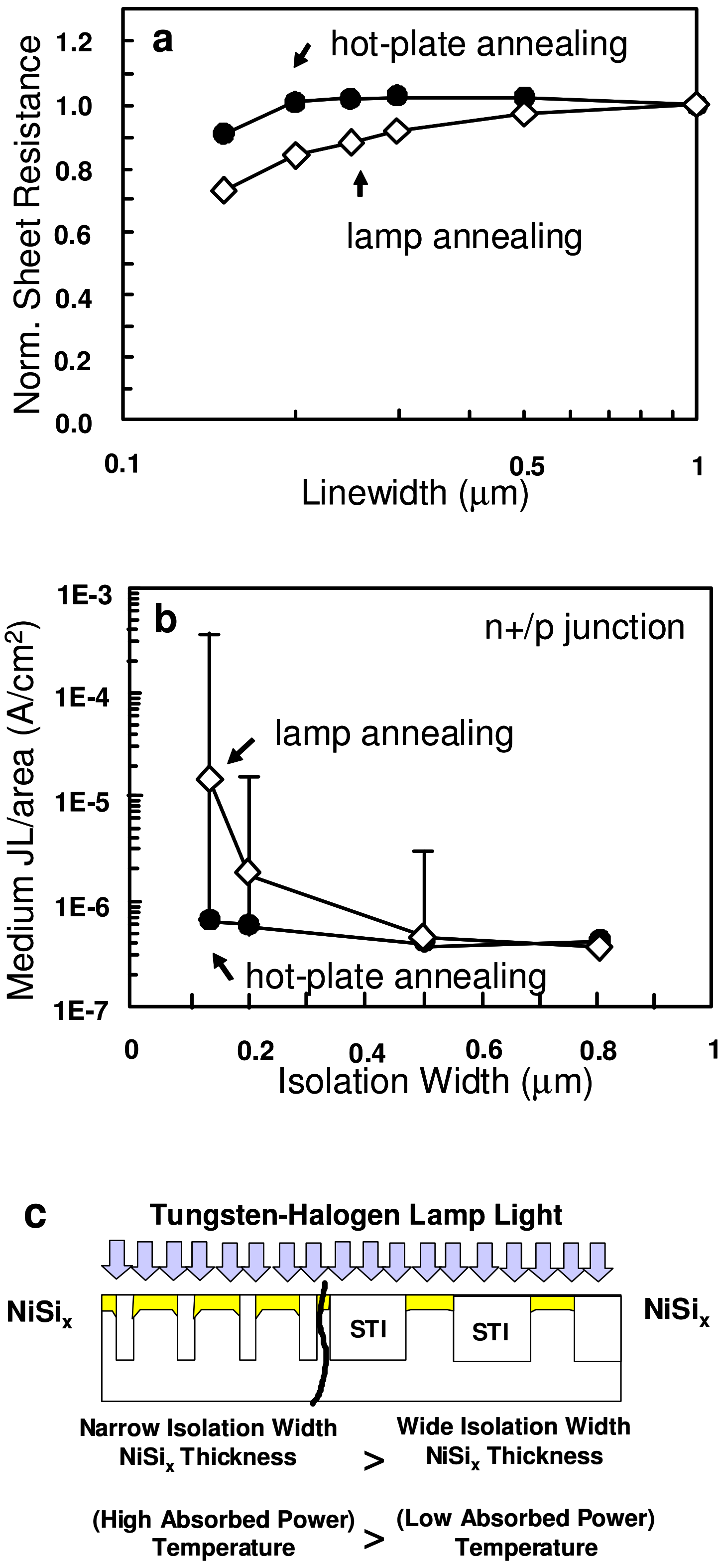

Figure 6. Normalized sheet resistance (a), junction leakage (b) characteristics of Ni-silicided small Si island n^+/p junctions and illustration of reaction mechanism (c) in ref. 9.

In principle, a preheated isothermal cavity can be a better approach to reduce the pattern effect and stabilize the process results. In an isothermal cavity at up to 1200°C, where most thermal processing is done for Si, wafer heating is accomplished by a combination of; natural convection, conduction through gas, and some contribution from IR radiation from the heated cavity. In addition, temperature overshoot at macro and micro level is not possible. In applications where process windows are small, the reduced uncertainty of the nearly isothermal cavity approach for thermal processing of advanced devices has significant advantages in uniformity, process control and repeatability as reported previously. (10-12)

Summary

Diffraction characteristics of patterned wafers with various pattern size and density were theoretically calculated. The possibility of diffraction originated local heating in a conventional lamp-based RTP system was raised as potential process variation and critical dimension control issues. The impact of diffraction originated local heating was estimated based on diffraction theory. Previously reported experimental results from an independent study were analyzed as a sample case of diffraction originated local heating. A preheated isothermal cavity approach was proposed to effectively reduce the pattern effect and stabilize process results.

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