Effects of Laser Drilling through Silicon Substrate on MOSFET Device Characteristics

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Abstract— The effects of laser drilling through silicon substrate formed by femtosecond laser on n-type MOSFET device characteristics are investigated. The tested MOSFET device structures are fabricated using the commercial 130-nm process. Through via holes and laser scanning line affect the device characteristics, such as drain current and threshold voltage, depending on the distance between the location of the drilling. The device degradation and variation along with a distance from the holes or the line are examined and the device characteristic variation is analyzed to determine the reliability of MOSFET devices against laser drilling damage.

BACKGROUND

Laser is widely used for ablation solid material precisely. For example, in TFT process, laser is used to cut the glass substrate to separate each module. Femtosecond laser emits extremely short pulses on the order of a few femtoseconds. This laser can process fast because it delivers a lot of energy in very short time. With this advantage, we can drill silicon substrate faster than other method, such as reactive ion etching (RIE) for through silicon via (TSV) application. Thus, in some applications, such as MEMS structure fabrication process, laser drilling can be a better solution. Some research groups are working on the laser drilling process to establish new and efficient fabrication method [1]. Many results present about MOSFET performance degradation by proton irradiation and curing by thermal annealing [2]. However, this process can accompany with laser damage effect and its mechanism is not currently identified. In this paper, the characteristic variation of MOSFET devices, such as drain current and threshold voltage, impacted by laser drilling is examined. The commercial 130-nm process is used for the fabrication of the MOSFET test structures where Aluminum is used for electrodes, pads and other metal connections. The two types of laser drilling techniques, the through via hole (TVH) and the laser scanning line (LSL), are performed. The measured current-voltage (I-V) data before and after laser drilling are used to analyze the effects on the characteristic variation of the MOSFETs.

METHODS

A. Experiments

We investigated the effect of laser drilling with two dies of n-type MOSFET. Each die has 21 n-type single MOSFETs and several de-embedding patterns. The first die has two TVHs on the right side of MOSFET devices. The second die has one laser scanning line with one TVH across the devices. Fig. 1 shows the laser process result and SEM images of the TVHs. As we can see in the SEM images, thermal migration is occurred near the TVH. From these images, we can conclude that quite large thermal energy is applied when the laser is irradiated. The effect of the laser damages depending on the distance between the drilling location and the device. Thus, the test devices for each die are categorized with 3 groups (A, B, and C) depending on the distance.

B. Femtosecond laser

In this work, the femtosecond laser micromachining system with a pulse duration of 184 fs, a repetition rate of 1 kHz and a pulse energy of 1 mJ at 785 nm wavelength was used for the hole drilling of the silicon plates. When the holes were drilled with this femtosecond laser system, the laser energy per pulse was adjusted to about 113 \( \mu J \), the focused laser beam spot was scanned with a velocity of 1 mm/s, and also the error margin of the hole diameter was controlled to within \( \pm 1 \mu m \).

C. Measurement

In this study, DC characteristics of MOSFET are measured. \( I_D-V_D \) and \( I_D-V_G \) characteristics are measured and threshold voltage is calculated from the graph. The linear part of \( I_D-V_G \) graph is fitted using linear fitting tool to get threshold voltage [3]. The DC characteristics are measured using HP4145B parameter analyzer.
The main degradation mechanism is occurred due to the difference of channel region vacancies and defects. Large energy is applied to whole die when during the laser drilling process. Based on several previous studies about radiation damage and x-ray damage, laser damage affects in similar way [2, 4]. After the laser drilling, drain current, transconductance (not shown here), and threshold voltage of the MOSFETs are increased. This phenomenon seems the combination of hole trapping at Si/SiO₂ and electron trapping at oxide region [5]. In this experiment, TVH and LSL damage on substrate cause similar degradation effect on the previous study. As the holes are trapped near Si interface, gate controllability is reduced. However, drain current is increased due to the trapped electrons in the oxide that can be a leakage path. As a result, the devices place near TVH or LSL, drain current and threshold voltage increased more than that of the device located far from damages as we can see in Fig 2, 3, 4, and Table 1. Fig. 2 and Table 1 are result about drain current increase and threshold voltage increase of die 1 after drilling. Fig. 3 and Fig. 4 show the similar result of die 2.

As a result, we can conclude that the degradation mechanism of laser drilling is quite different from other physical stress. The drain current, transconductance, and threshold voltage are all increased. This increment show the reliability of device is decreased because the gate oxide can be easily wear-out due to the trapped electrons and trap sites generated at the interface can accelerate the device aging.

REFERENCES


Table 1

<table>
<thead>
<tr>
<th>Set number</th>
<th>Before drilling</th>
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<tr>
<td>Group 1-A</td>
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<td></td>
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<tr>
<td>Group 1-C</td>
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<td></td>
<td>Standard Deviation 0.0039</td>
<td>0.0034</td>
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</table>

Fig. 2 Normalized drain current difference of devices in die 1. Set 1 is the nearest devices from TVHs. (The number in parentheses under each group is the average distance from TVHs.)

Fig. 3 Drain current characteristics along with distance in die 2. (a), (b) and (c) are ID-VD graphs of Group A, B, and C. (d), (e) and (f) are ID-VG graphs of Group A, B, and C. (Group A is most close to LSL, and Group C is most far from the LSL. (a), (b), and (c) are measured under VD=1 V. (d), (e), and (f) are measured under VG=1 V.)

Fig. 4 Threshold voltage difference of die 2. The difference is calculated as Vth_after drilling - Vth_before drilling. (The number in parentheses under each group is the average distance from LSL.)