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고압 실리콘 p-i-n 스위칭 소자의 안정도

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Stability of High-Voltage Silicon P-I-N Switches

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Abstract - The possible origins of instabilities observed in high-voltage p-i-n devices were investigated. It was concluded that the temporary changes of electrical characteristics may be due to the changes of the physical parameters of gold acceptor, while the permanent changes are due to process-related factors.

1. Introduction

The primary advantages of optically controlled semiconductor switches compared to other high power switches are their jitter-free, fast switching and electrical and thermal isolation between switching and control circuits. Recently junction switches have received much attention. Silicon p-i-n diode switches have been reported to deliver high electrical pulse power.[1-3] However, the reliability or stability of high-voltage p-i-n switching devices has been a controversial subject because a number of different types of electrical and thermal instabilities in p-i-n devices were observed by many workers, depending on external or internal conditions. Until now the causes of these instabilities have not been clear.

First, the instabilities of the I-V characteristics of gold-doped p-i-n devices observed in this work are described. Then the possible origins of these instabilities are discussed. The pre-breakdown and post-breakdown oscillations are not included because they occur only under special conditions.

2. Instability of Silicon P-I-N Switches

Four different instabilities on current-voltage characteristic of device were observed in this work.

The first example type of instability is shown in Fig.1. This device exhibited a gradual shrinking of threshold voltage with time when they were in the ON-state for a long period. After the device was allowed to cool, the threshold voltage recovered to the original value.

Figure 2 shows a permanent change of threshold voltage. This device showed first a high threshold voltage of 395 V, as shown in 2(a). The threshold voltage stabilized to 210 V after several switching operations.

The third example of instability is shown in Fig.3. Many long channel devices initially had high threshold voltages of about 600-800 V. Soon after switching, however , they showed the current-voltage characteristic in Fig.3, which illustrates two features different from the normal I-V curve.

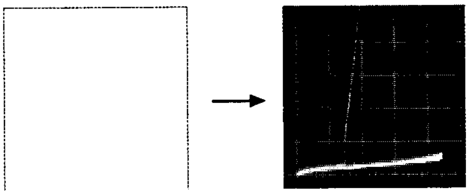

Fig.1 Switching voltage shrink of device in an hour after switching.

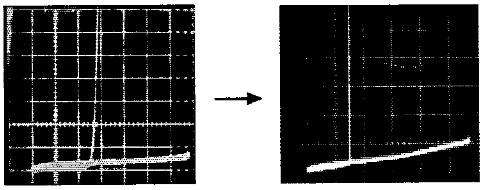

Fig.2 Permanent change of I-V curve of device.

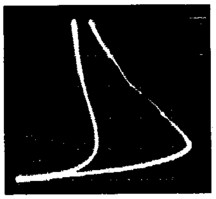

Fig.3 The I-V curve trace of device exhibiting thermal instability.

Figure 4 shows the forth example of current-voltage curve instability. The current-voltage curve in Fig.4(a) shows the threshold current much higher than the holding current, which is sometimes observed in high off-state current devices. After a while the on-state voltage became gradually higher than the original value, whereas the threshold voltage was reduced. This instability rarely occurred.

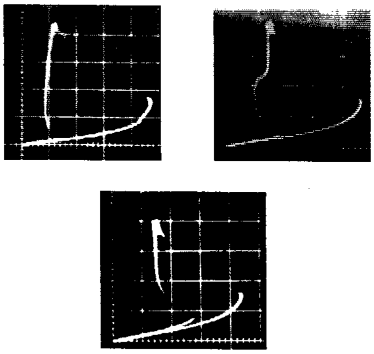

Fig.4 On-state voltage instability of device.

2.1 Room temperature motion of gold-related centers

The instability of p-i-n devices has been attributed to the gold atoms themselves because (a) gold is a fast diffuser and (b) the gold diffusion process is very difficult to control. Gold is well known as an extremely rapid diffuser in silicon, with a diffusion coefficient about 5 orders of magnitude larger than those of boron or phosphorous at low and high temperature. At this point, there is little available information on the low temperature diffusion coefficient of gold in silicon. Pearton et al. [4] observed the room temperature motion of gold-related centers in reverse-biased silicon n^+p injection diodes using deep level transient spectroscopy(DLTS). According to their calculation, the room temperature mobility of gold-donor in gold-doped p-type silicon is $\mu_{Au} = (7.8 \pm 3.2) \times 10^{-15}$ $cm^2/V-s$ at 25 ℃ for maximum electric field strength of 6.9×10^4 V/cm, the corresponding diffusion coefficient is $D_{Au} = (2.0 \pm 0.8) \times 10^{-16}$ cm^2/s where the singly charged defect was assumed. Surprisingly, under the same condition, however, no movement was observed for the gold-acceptor center in gold-doped n-type silicon. In order to show how seriously a device is affected, we calculated the room temperature motion of the gold-related center using the diffusion constant and mobility of gold donor given in Ref .[4]. The results are given in Table 1 and 2. Thus, the room temperature motion of the gold-related center is negligible compared to channel length(usually larger than 100㎛), but the drift length under a high field is considerable.

Table 1 Diffusion length of gold in Si at 25℃.

Time t	Diffusion length at 25℃ L_d (㎛)
1 month (30 days)	0.176 - 0.269
6 months	0.432 - 0.660
12 months	0.864 - 0.940
24 months	0.864 - 1.320

Up to this point , we calculated the diffusion length L_d at room temperature and the drift under high electric field. The calculated values show the possibility that the room temperature motion of gold atoms up to a high field may change the distribution of the charged gold centers with time, resulting in the long-term instability of the p-i-n device, if the device remain in operation for a long time, at least several months.

Table 2 Drift length of gold in Si under high electric field.

Time t	Diffusion length under high field L_{drift} (㎛)
1 month	1.59 - 3.79
6 months	9.51 - 22.75
12 months	19.02 - 45.50

In view of the facts discussed above, it is difficult to believe that only the gold motion at room temperature may cause the threshold voltage to shrink as observed in p-i-n devices.

2.2 Thermal instabilities

The thermal instabilities of p-i-n devices can be broadly classified into three categories: (a) the temporally change of characteristic (Fig.1). In this case, the original characteristic will return after the device is cooled. (b) Permanent change of characteristic (Fig.2). (c) Irreversible demage to device, i.e., the device will be destroyed. The causes of thermal instabilities are not clear thus far. No attempt was made to investigate the thermal instability. Here, the possible origins are simply speculated. The instability shown in Figs. 1 and 2 occurred more often in the high on-state and off-state current devices than in low on-state and off-state current devices. In fact, the p-i-n devices generate heat due to the power dissipation in its transient and steady-state operation conditions. Here, the gold motion due to device heating is considered. Beyond the negative differential resistance region, the device current is highly increased and current-voltage characteristic is nearly vertical. Most of current flows through a small cross-section. Thus the semiconductor becomes electrically heterogeneous as excess current flows through a small cross-section. Such current filaments consist of quasi-neutral regions, flooded with electrons and holes in almost equal numbers. The filament temperature is very high due to localized heating by excess current. According to Bob Smith[5], the observed filament temperature ranged from 82 ℃ to 578 ℃. For normal device operation with power less than one watt, the filament temperature was between 100 ℃ and 200 ℃. This high temperature will heat up the device.

Since the gold atom is a fast diffuser in silicon, as mentioned earlier, it is entirely possible that device heating within the current filament may be the cause of gold redistribution during operation. Under this assumption, we again calculated the diffusion length at temperatures above than room temperature. The current filament was assumed to be stable.

The usual expression for the temperature dependence of the diffusion coefficient, is given below

$$D = D_0 \exp(-\delta E/kT) \quad (1)$$

D_0 : Diffusion coefficient extrapolated to infinite temperature from temperature high temperature measurement. δE : Activation energy of diffusion, $k = 8.6183 \times 10^{-5}$ eV/° K. where the value of D_0 and δE depend on the assumed diffusion mechanism of gold. Gold diffusion in silicon is known to occur by several mechanism. recently the kick-out mechanism is preferred. For consistency with Ref.[4], however, the dissociative mechanism is assumed here. For the dissociative mechanism, $D_0 = 10^{-4}$ cm^2/s and $Q = 0.9$ eV from Ref.[4]. the calculated diffusion length for each temperature is listed in Table 3.

Table 3 Diffusion length of gold for various temperature.

Time (hr.)	Diffusion length(μm)			
	100℃	200℃	300℃	400℃
1	0.158	3.05	20.95	80.49
5	0.353	6.82	40.86	181.0
10	0.499	9.64	66.27	255.97

From the above calculation, a signification change of threshold voltage and holding voltage may be expected.

A number of important questions have became apparent. The first question is the fact that the threshold voltage shrinks as shown in Fig.2, usually over a several second period or sometimes after several switching operations. time period is not enough for a significant movement of gold at low temperature.

As shown in Fig.1, the original characteristics returned after the devices were allowed to cool. That is, this instability is reversible for some devices. This is incompatible with the fact that motion of gold is a permanent alteration in the physical characteristics of the device (sometimes irreversible damage to the device).

2.3 Fabrication-related instability

We believes that most of instabilities observed in p-i-n devices (especially permanent changes of characteristics observed for planar-type p-i-n devices fabricated in this lab.) are due to process-related factors, because:(a) Two devices on the same chip show different instabilities.(b) The instabilities due to gold are not observed in p-n junction devices. (c) The guarding and compound electrode devices are more reliable and stable. In conclusion, instabilities cause by processing factors can be accelerated by thermal or electrical stress, leading to permanent changes of device of device characteristics or irreversible damage to devices. As mentioned earlier, we must establish the optimal fabrication process schedule for p-i-n devices. Then thermal instability mechanism should become known. This could be done by measuring the activation energy for thermal instability.

3 Conclusions

Various instabilities on the current-voltage characteristics of p-i-n device were observed. The possible origins of these instabilities were investigated and discussed somewhat quantitatively in more details in terms of room temperature of gold centers, thermal instability, and fabrication-related factors. The instability can be classified into two categories: temporary and permanent changes for device characteristics. The former may be a temperature effect on the physical parameter of the mechanism responsible for the switching characteristics of p-i-n devices. On the other hand, we believes that the permanent change of characteristics which often occurs is due to process-related factors. Instabilities caused by processing factors can be accelerated by thermal or electrical stress, leading to permanent change of device characteristics or irreversible damage to devices. Moreover, since the i-base region of p-i-n devices has a very high resistivity, even small amounts of contamination on the surface of SiO_2 would cause inversion of this region and formation of channels with surface leakage current flowing. This current can reduce the threshold voltage and increases the power dissipation, leading to device to device instabilities.

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