The Electrical Properties of Polycrystalline Silicon Resistors

(다결정 실리콘 저항의 전기적 특성)

朴鍾泰,* 崔民成,** 李文基,* 金鳳烈*

(Jong Tae Park, Min Sung Choi, Moon Key Lee and Bong Ryul Kim)

要 約

높은 면저항(Rs, 350Ω/□-80kΩ/□)을 갖는 다결정 실리콘 저항을 바이폴라 공정조건에서 boron 이온 주입방법에 의하여 제작하였다. 본 실험에서는 Rs가 도핑농도에 따라 변하는 것과 열처리가 Rs에 미치는 영향, 다결정 실리콘 저항의 온도계수(TCR), 다결정 실리콘의 두께에 따른 Rs의 변화 및 공정과 공정사이의 Rs편차에 관한 연구를 하였다.

Abstract

High value sheet resistance (Rs, 350Ω/□ -80k Ω/□) boron implanted polysilicon resistors were fabricated under process conditions compatible with bipolar integrated circuits fabrications. This paper includes studies of sensitivity of Rs to doping concentration, the effect of thermal annealing temperature on Rs, temperature coefficient of resistance (TCR), the effect of polysilicon thickness on Rs and the Rs variation within a run and between runs.

I. Introduction

Polycrystalline silicon has wide application in integrated circuits for high value resistor. High sheet resistivity material has the advantage of not only decreasing the power consumption but increasing both chip density and performance. Its usuage is, however, greatly restricted by some major problems of reproducibility associated with the polycrystalline nature of the material. These problems must be solved before any product application is possible.

One problem is the great sensitivity of Rs to the doping range of resistor application (1, 2). This raises the reproducibility and tolerance concerns for the product. Another possible problem is the sharp increase of temperature dependence of resistivity on the doping concentration in the range of interest (2). The characteristic behavior of polysilicon resistor has been explained by the widely accepted carrier traping theory (1-5). The first quantitative theory of carrier traping was developed by Seto (1). This model explains the electrical conduction of polysilicon by the thermionic emission of carriers over the grain boundary potential barrier built from the charged traps and space charges of the depleted zone near the grain boundaries. Seto's theory was later modified by various investigators (2-5); the basic assumption was not changed, but they added a metallurgical grain boundary

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*正會員, 延世大學校 電子工學科

(Dept. of Elec. Eng., Yonsei Univ.)

**正會員, 金星半導體株式會社 研究所

(Gold Star Semiconductor Ltd, R&D)

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scattering potential in addition to the space charge potential barrier (2,5). To explain the electrical behavior, they included quantum mechanical thermionic field emission of carrier through the modified potential barrier explained above as well as thermionic emission over the barrier (5).

In this paper, the controllability of sheet resistance of boron implanted polysilicon resistor is described with the sensitivity of Rs to doping concentration, the effect of annealing temperature on Rs, temperature coefficient, and the effect of polysilicon thickness on Rs and their reason are qualitatively explained.

II. Experimental Procedures

The flow of experimental procedures is shown in Figure 1. A 3700 Å of thermal oxide was grown on P type silicon wafer (10-20Ω -cm) at 1000°C, for 50 min. After LPCVD (low pressure chemical vapor deposition) polysilicon was deposited (3000 or 4000 Å) by silane decomposition at 625°C, a thermal cap oxide (400 Å) was grown on top of the polysilicon at 900 °C, for 45 min. Boron was implanted for polysilicon resistor at 50-75 KeV, and 1.8E14-4.4E14 cm^{-2} in dose was reported to be small compared to phosphorus or arsenic (6). The anneal was done in the range of 800-1100°C for 64 or 81 minutes in the N_2 ambinent. Some of these conditions simulated the base and emitter anneal heat cycle of an actual bipolar process. The resistor was defined by photolithography and reactive ion etching (RIE) of oxide and polysilicon. CVD silicon nitride was deposited and resistor contact area was defined and PtSi was formed as a contact metallurgy.

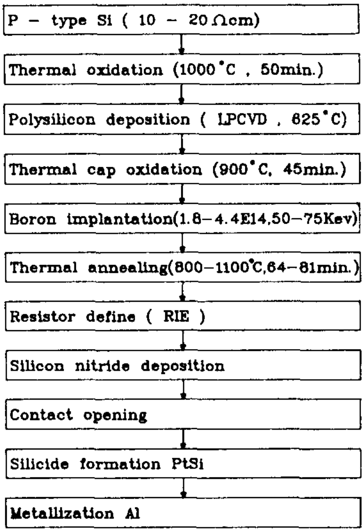

Fig. 1. The flow chart of sample preparation.

Al-4%-Cu was deposited as the conducting metal after which a further anneal was done at 400°C for 1-2 hour in N_2 ambient. The shchematic diagram of test vehicle is shown in Fig. 2 (L=100 μm, W=100 μm). Rs was measured at two current levels (25 μA, 50 μA) to measure the voltage coefficient of resistance (VCR). VCR was zero as expected. Twelve to twenty-four sites of each wafer were measured of Rs across the wafer at 25°C and 125°C.

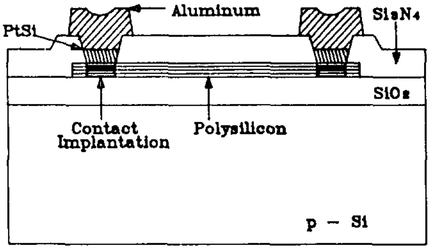

Fig. 2. Schematic cross section of a polysilicon resistor.

III. Experimental Results

1. *Effect of Doping Concentration and Annealing Temperature on Rs.*

Table 1 gives the effect of doping concentration and resistor annealing temperature on sheet resistance (Rs). A flat profile of boron concentration across the polysilicon film was assumed after anneal and was verified by secondary ion mass spectroscopy (SIMS); the doping concentration was calculated from the thickness and ion implantation dosages. The polysilicon film thickness remaining after cap thermal oxidation, was measured by FTA (film thickness analyzer) after stripping the oxide. The Rs value with its standard deviation and temperature coefficient of

Table 1. Effects of doping and annealing temperature on sheet resistance (Rs)

Lot #	Doping Concen. (cm^{-3})	$R_s \pm \sigma$ (KΩ/□)	25-125 ℃ TCR (%)	Film Thickness (Å)	Anneal Temp (℃)	Anneal Time (Min)
4413	5×10^{18}	46.8± .93	−55.0	3000	1000	81
0627	8×10^{18}	10.0± .31	−32.2	3000	1000	81
0632	8×10^{18}	10.7± .15	−33.9	3000	1000	81
0712	8×10^{18}	12.3± .31	−34.4	3000	1000	81
0627*	8×10^{18}	9.92± .30	−31.7	3000	1000	81
0712*	8×10^{18}	10.22± .27	−32.0	3000	1000	81
2736*	8×10^{18}	9.17± .16	−33.2	3000	1000	81
4413	1×10^{19}	7.10± .11	−30.0	3000	1000	81
0627	1×10^{19}	6.40± .17	−26.9	3000	1000	81
0627*	1×10^{19}	6.53± .197	−27.0	3000	1000	81
0415	2×10^{19}	1.80± .017	−12.4	3000	1000	81
0307	2×10^{19}	1.72± .03	−13.1	3000	1000	81
2736	2×10^{19}	1.67± .01	−13.0	3000	1000	81
0707	5×10^{18}	26.6 ± .48	−51.9	4000	950	64
0707*	5×10^{18}	13.6 ± .23	−40.3	4000	950	64
0706	8×10^{18}	7.9 ± .12	−36.4	4000	950	64
0706*	8×10^{18}	4.67± .07	−24.3	4000	950	64
0307	2×10^{19}	1.0 ± .01	−10.1	4000	950	64
0712	5×10^{19}	.3 ± .004	+ 8.6	4000	950	64
0707	5×10^{18}	81.6 ±1.9	−62.2	3000	800	81
0706	5×10^{19}	.71± .01	− 5.4	3000	800	81
0715	5×10^{18}	11.05± .25	−36.9	3000	1100	81
0715	1×10^{19}	2.69± .06	−16.8	3000	1100	81
0706	2×10^{19}	1.0 ± .012	− 3.9	3000	1100	81
0706	5×10^{19}	.35±0.004	+13.	3000	1100	81

*Represent the wafers which did not receive contact ion implantation σ : standard deviation

resistance (TCR) between 25°C and 125°C are contained in the table for different annealing temperature and time. As seen in this table, the Rs tolerance within a run is less than 3% for all the samples. It is also shown in this table that run to run variation in Rs for 2 or 3 different runs is less than 10% for 2-10 K Ω/□ resistor. Figure 3 plots log Rs vs 1/doping concentration for different process conditions (annealing temperature, time and polysilicon thickness). It shows that Rs is strong function of ion implant dose (nearly exponential), as reported previous investigators (1, 7). For the same amount of doping concentration, the Rs value is higher for the samples which were annealed at low temperature.

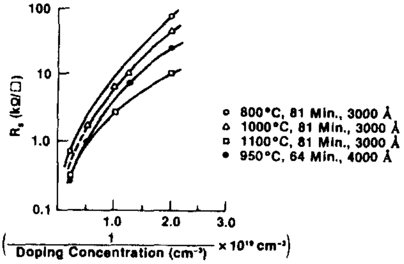

Fig. 3. Effect of doping and annealing temperature on sheet resistance (Rs).

However, the sample of 4000 Å polysilicon thickness annealed at 950°C showed lower Rs than the 3000 Å samples annealed 1000°C. The grain size of polysilicon fiim measured by transmission electron microscope (TEM) was about 600 Å up to 1000 Å annealed for all the doping range of this experiment. Negligible effect of boron doping concentration on the polysilicon film grain growth was also reported elsewhere (8). The grain size of 300 Å polysilicon annealed at 1100°C for 1 hour was about 1500Å for the samples of 10E20/cm^3 doping concentration.

2. *Effect of polysilicon Thickness on Rs*

In Fig. 3, it was shown that 4000 Å thick polysilicon samples has lower Rs than 3000 Å thick samples for a comparable amount of anneal. In real device fabrication, a few percent of run to run derivation from the target polysilicon thickness is usually expected. Table 2 and Fig. 4 show the effect of run to run poly-

Table. 2. Effect of polysilicon thickness on Rs.

JOB #	DOSE (cm^{-2})	THICKNESS (Å)	R_s (KΩ/□) $\pm\sigma$
06	1.8×10^{14}	2809	12.47± .20
0632	1.8×10^{14}	3001	10.7 ± .15
	1.8×10^{14}	3255	10.39± .20
0712	1.8×10^{14}	2963	12.25± .31
0627	1.8×10^{14}	3129	10.0 ± .31
4413	2.2×10^{14}	2951	7.1 ± .11
0627	2.2×10^{14}	3001	6.4 ± .17
0415	4.4×10^{14}	2993	1.82± .017
0307	4.4×10^{14}	3065	1.72± .03

silicon thickness variation on Rs reproducibility. The target thickness was 3000 Å for every job except for job 0632 aiming at 2800 Å, 3000 Å, and 3200 Å. Rs vs polysilicon thickness is plotted in Fig. 4. The three different curves in this Figure represent the three different dosages given in Table 2. It is seen that a strong relationship exists between Rs and the film thickness, i.e., the smaller the thickness, the higher the Rs. It is also noticed that the sensitivity of Rs to film thickness is increased for the lower doping concentration and for the thickness below 3000 Å (actual polysilicon thickness after thermal cap oxidation would be about 2000 Å). Therefore, it is thought that polysilicon thickness should be at least 2000 Å at increase the Rs reproducibility in real device fabrication.

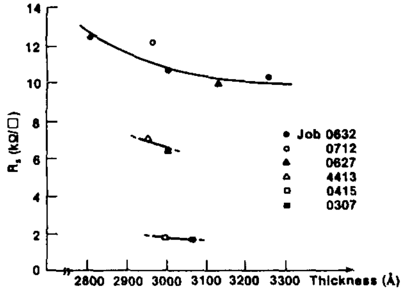

Fig. 4. Effect of polysilicon thickness on Rs.

3. *Temperature Coefficient of Resistance (TCR)*

Fig. 5 show the plot between Rs and TCR (between 25°C-125°C in percent) from the data contained in Table 1. Fig. 5 demonstrates that TCR is a function of sheet resistance and the film thickness, but not of other process variables (dose, annealing temperature and time). The 4000 Å samples appear to have slightly lower TCR than the 3000 Å samples. The magnitude of TCR increases (becomes more negative) as Rs increases. Note that the sign of TCR changes from negative to positive at very high doping concentration.

IV. Discussions

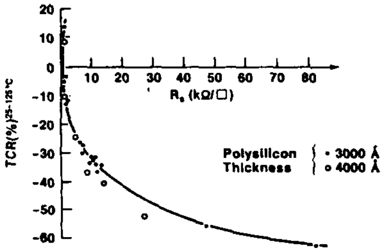

Fig. 5. Temperature coefficient of polysilicon resistors (TCR).

Most of the electrical characteristics observed in this work can be explained by the existing grain boundary carrier trapping theory (1-5). The high sensitivity of sheet resistance to the doping concentration, particulary at lower concentration (see Fig. 3), can be understood by the fact that the grain boundary resistvity is an exponential function of the grain boundary potential height until bulk resistivity becomes more important than the grain boundary resistivity at high doping.

1. *Effect of Annealing Temperature on Rs*

Kamins (9) reported that polysilicon film deposited at around 600°C by the LPCVD method and done by phosphorus-ion implantation showed much higher Rs for the sample annealed at low temperature than those annealed at higher temperature. He related this to the grain growth at the higher annealing temperature (greater than 1000°C). Similary, the high sensitivity of both Rs and the rate of change of Rs with dose to the annealing temperature (Fig. 3) is thought to be because of an increase in the active carrier concentration due to high temperature heat cycle. An enhanced grain size following 1100°C anneal may explain the big reduction of Rs from 1000°C anneal compared to the smaller Rs reduction between 800°C and 1000°C anneal sample where no significant grain size change was noticed from TEM observations.

2. *Film Thickness Effect on Rs*

The sharp decrease in the resistivity of doped polysilicon with the increase of film thickness was reported by previous investigators for both thick film (greater than 2 μm, ref 3) and thin film (less than 0.5 μm, ref 10). The increase in carrier mobility with film thickness explains that. The same phenomenon is still seen for the small thickness fluctuations which are commonly encountered during a manufacturing operation (see Fig. 4). For the same dose, Rs should be independent of film thickness unless mobility is a function of film thickness. The change in grain size and carrier charge trap density is thought to be the reason why the mobility varies with the film thickness. Since the grain boundary trap sites can be saturated more easily at higher doping concentration, the sensitivity of Rs to the film thickness is decrease with increase in doping concentration.

3. Temperature Coefficient of Resistance (TCR)

It was found by previous investigators (2) that a specific resistivity (9) has a specfic activation energy (Ea) independent of the polysilicon resistor fabrication process; the higher the ρ, the larger the Ea, where Ea is defined as:

$$Ea = \ln \rho \, / \, (1/kT)$$

This can explain the observed TCR increase with Rs increase in Fig. 5. For the thicker film, the ρ value is greater than for a thin film with the same Rs, therefore the TCR should be higher for the thicker film. This effect seems apparent for Rs values greater than 5 KΩ/☐ in Fig. 4. Below 5 KΩ/☐, the trend is not clear. This may be due to the very high sensitivity of TCR to Rs. At very high doping concentration, the bulk resistivity becomes more important than grain boundary resistivity; than, the dependency of resistivity on temperature becomes like single crystalline silicon and the sign of TCR changes from negative to positive.

V. Conclusions

Boron ion implanted polysilicon resistor (350 Ω/☐ –80 KΩ/☐) were fabricated under conditions compatible with bipolar integrated circuit fabrication. High sensitivity of Rs to the ion implantation dose and annealing temperature was observed. Rs tolerance within a run was less than 3% for all samples and run to run reproducibility of less than 10% (up to about 2000 Å in this work) exists under which reproducible Rs control is difficult. The sign of TCR was negative except for the highly doped samples, and the magnitude of TCR increased with the increase in Rs independent of boron implantation dose and heat cycle. Its values measured between 25-125°C was about 15% and 62% for 2 KΩ/☐ and 80 KΩ/☐ resistor respectively. At very high doping concentration (about 5E19 atoms/cm^3), the sign of TCR changed from minus to plus.

TCR was larger (more negative) for thicker film. Therefore, a compromise should be made between TCR and Rs control to determine the optimum film thickness in designing high value Rs polysilicon resistors. It is believed that a certain amount of boron atoms in the polysilicon film do segregate to the grain boundaries during the anneal (900°C). This means that the sequence of the heat cycle as well as the anneal temperature is equally important to determine the final resistor value.

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