EFFECT OF ULTRASONIC TREATMENT OF SILICON IMPATT DIODES, POWER SCHOTTKY DIODES AND ZENER DIODES ON THEIR ELECTRICAL CHARACTERISTICS

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Ultrasonic treatment of packaged silicon IMPATT diodes and power Schottky diodes is performed. It results in both a substantial reduction of the diode reverse current and improvement of the $I—V$ curve stability. The results obtained evidence that ultrasonic treatment at room temperature stimulates a substantial modification of the impurity-defect structure of $p—n$ junctions in the diodes studied. An ideal Shockley diode is realized in a silicon $p—n$ junction as a result of the current mechanism changing from generation-recombination to the diffusion one. For comparison, the electrical characteristics of silicon alloy Zener diodes exposed to ultrasonic treatment are also studied.

Introduction

It is known that the manufacturing technology of diffusion $p — n$ junctions has made great strides. However, the problems concerning the excess current nature still remain of interest to many production engineers. These problems are especially urgent in the manufacturing technology of microwave impact-avalanche and transit-time (IMPATT) diodes. Here, the facet side face is comparable to the diode acting area. Thus, excess currents are determined by the processes occurring both in the bulk and at the side faces of $p—n$ junctions [1 — 3]. For the packaged diodes (amounting to the final product), one can reduce, on occasion, excess currents and improve the avalanche breakdown uniformity using either ^{60}Co γ-irradiation [4] or electrothermal training [5]. In [6], we reported on the improvement of the avalanche breakdown uniformity in silicon double-drift IMPATT diodes exposed to ultrasonic treatment. In [7, 8], a mechanism of acoustoelectric conversion in $p—n$ junctions was discussed. It was related mostly to a semiconductor gap change due to ultrasonic treatment (the voltage at an ultrasonic transducer was about 89 V).

However, the effect of ultrasonic treatment on excess currents (and their stability) in silicon microwave diodes of small diameter, as well as in power Schottky diodes and Zener diodes, practically has not been studied. For the above devices, a possibility to control stability of the reverse branches of $I — V$ curves is of great importance. The reason for this is that the output parameters of IMPATT diodes (as well as characteristics of other types of diodes where the reverse branch of an $I — V$ curve is the operating one) depend on the excess current value.

Here, we present some results of our investigations of the ultrasonic treatment effect on the electrical characteristics (including the reverse current stability) of packaged silicon IMPATT diodes, power Schottky diodes, and Zener diodes.

Experimental Details

We studied silicon drift diffusion $p^+—n—n^+$ IMPATT diodes. They were fabricated using boron diffusion from the vapor phase (at a temperature of 1050 °C) into a silicon epitaxial $n—n^+$ structure. The diffusion process took from 30 to 45 min. The $p—n$ junction depth was 0.6 μm. The boron concentration in the p^+ layer was 10^{20} cm^{-3}, while that of phosphorus was $3 \cdot 10^{16}$ (in the n layer) and 10^{19} cm^{-3} (in the n^+ substrate). The $n\,(n^+)$ region thickness was 1.5 (300) μm.

After fabrication, the diodes (30 μm in diameter) were installed into IMPATT diode packages. We studied the IMPATT diodes of two types, namely, (i) with excess leakage currents, (ii) with unstable reverse branches of $I—V$ curves. For comparison, the electrical characteristics of silicon alloy Zener diodes of the KC 620 — 680 type (whose breakdown voltage was 14 — 15 V) were also studied. The diodes were exposed to ultrasonic treatment and were held in vacuum (pressure of 10^{-4} Pa). The ultrasonic treatment was performed at a temperature of 50 °C using piezoceramic transducers; the frequencies used varied from 0.11 to 14 MHz (in analogy with the mode used in [6]). The ultrasonic power applied to the samples studied could be varied by changing the radiofrequency voltage feeding the ultrasonic transducer.

We have also studied both the forward and reverse branches of $I—V$ curves for silicon power Schottky diodes before, as well as after, ultrasonic treatment. The Schottky barrier was formed using chromium thermal evaporation onto the as-etched surface of the silicon n—n^+ structure. The n (n^+) layer thickness was 15 (350) μm, and the dopant (phosphorus) concentrations in these layers were $\sim 10^{14}$ and $5 \cdot 10^{18}$ cm^{-3}, respectively. The active areas whose surface was ~ 14 mm^2 were formed using photolithography. To provide the avalanche breakdown uniformity in the power Schottky diodes studied, a special protecting ring has been formed along the barrier perimeter. This ring was a MIS structure similar to that discussed in [9]. The power Schottky diodes were mounted in metal-ceramic packages.

Results and Discussion

The I—V curves, as well as the reverse current (at a reverse bias voltage of 4 V) versus temperature curves, were taken in the 300 to 370 K temperature range, both before and after the treatment of the samples. Shown in Fig.1 are the reverse branches of I—V curves for the initial sample (curves *1*, *1'*). (The first measurement gave curve *1*; being repeated, it gave the curve *1'* which did not coincide with curve *1*). After the ultrasonic treatment, the repeated measurements gave the same reverse branches of the I—V curve as the first measurement; besides, the excess leakage currents disappeared.

The above discrepancy between the reverse branches disappeared also after holding the initial samples in vacuum (at a pressure of 10^{-4} Pa) for 20 min. This fact indicates that the leakage currents in the samples studied are surface currents by their nature. They could be related to the adsorption of impurities onto diode facets. It should be noted that keeping the packaged diodes out of doors for 3 months after holding them in vacuum led to the appearance of the above reverse current creep (but at lower reverse currents). Contrary to this, for the samples exposed to ultrasonic treatment, the I—V curves remained the same.

Initial IMPATT diodes of the second type were characterized by an excess reverse current that did not vary with time. Holding such diodes in vacuum resulted in the reverse current drop by several orders of magnitude. After keeping these diodes out of doors for 3 months, excess currents appeared again. This fact may serve as an evidence that an impurity adsorption occurred at diode facets. For such samples, ultrasonic treatment led, as a rule, to a substantial reduction of reverse currents. Keeping the samples out of doors for 3 months did not change the IMPATT diode I—V curves.

In the reverse voltage range from 0 to 8 V, all the samples, whatever the treatment type (holding in vacuum or ultrasonic treatment), demonstrated the reverse current independence from the voltage — i.e., the so-called saturation (diffusion) current. This fact

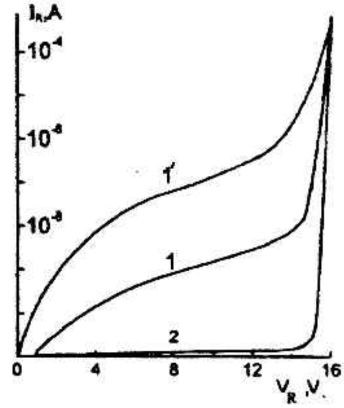

Fig.1. I — V curve reverse branches for a silicon IMPATT diode: *1*, *1'* — initial; *2* — after the ultrasonic treatment (5 V, 160 kHz, 1 h)

is an indication that the concentration of generation-recombination centers in the space-charge region of a p—n junction is insignificant. Another such evidence is the temperature dependence of the reverse current at the above voltages. The slope of this curve gives the value of the activation energy about 1.1 eV (i.e., about the silicon gap), and not the value which is characteristic of the generation-recombination current when the energy levels of the corresponding generation-recombination centers are near the silicon midgap (see Fig.2, curve *1* for the initial sample). One further evidence is that the ideality factor n for the forward branch of the diode I—V curve drops substantially (from $n \approx 2$ to $n \approx 1.05$) after the ultrasonic treatment (5 V, 160 kHz, 1 hour). This fact points to both a change in the charge transport mechanism for the forward branch of the I—V curve and a substantial decrease of the contribution from the recombination component of current. After the samples studied (held in vacuum) were kept out of doors for 3 months, the reverse current activation energy dropped, as compared to the preceding treatment (holding in vacuum — see Fig.2, curve *3*). Activation energies were also found from similar (the reverse current logarithm versus inverse temperature) curves taken for the diodes exposed to: (i) ultrasonic treatment, (ii) the same as in (i) followed by keeping out of doors for 3 months. In both cases, the activation energy values were the same (about 1.1 eV).

The results obtained indicate that the ultrasonic treatment of silicon IMPATT diodes almost completely removes the adsorbed impurities from the p—n junction side face. Contrary to this, holding the samples in vacuum seems to leave some impurities at this face. When the diodes are being stored, such impurities can become active and take up various ambient contaminants. From the near-avalanche parts of the

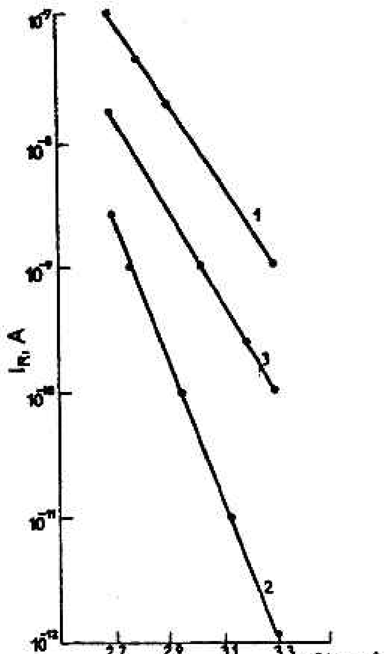

Fig.2. Reverse current logarithm versus inverse temperature curves (taken at a reverse bias voltage of 5 V) for a silicon IMPATT diode: *1* — initial; *2* — after holding in vacuum (10^{-4} Pa, 20 min); *3* — after holding in vacuum followed by keeping out of doors (3 months)

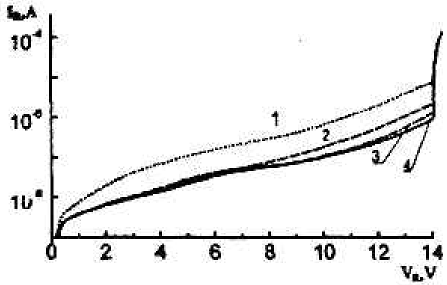

Fig.3. Reverse branches of *I — V* curves for a silicon alloy Zener diode — initial (*1*) and after the ultrasonic treatments: *2* — 2 V, 160 kHz, 1 h; *3* — the same as *2* plus 3 V, 160 kHz, 1 h; *4* — the same as *3* plus 5 V, 160 kHz, 1 h

I—V curves for such IMPATT diodes, one can conclude that the avalanche breakdown becomes more uniform after ultrasonic treatment (see also [6]). This may be a result of either reduction in the number of microplasmas or their complete disappearance.

For Cr—n—n^+—Si power Schottky diodes, we have calculated how their parameters change after different ultrasonic treatments. The corresponding results are given in Table. One can see that both the Schottky barrier height, φ_B, and avalanche breakdown voltage, V_B, did not change after ultrasonic treatments, while the ideality factor, n, somewhat dropped and the reverse current, I_R, decreased by a factor of about two. It should be noted that all the power Schottky diodes studied (initial samples, as well as those exposed to various ultrasonic treatments) demonstrated an uniform avalanche breakdown. A comparison between the above results to those obtained for parameters of silicon IMPATT diodes after similar ultrasonic treatments shows that the effect of these treatments is much more pronounced for diodes with small acting area, when there exists a considerable drain of defects to the surface. The mechanism of reverse current decrease in power Schottky diodes seems to be related to the ultrasound absorption by defect aggregations in the space-charge region. This makes possible a structural-defect ordering of such aggregations, and such an effect is more pronounced for diodes with small acting area [10].

Silicon alloy Zener diodes (whose acting area is an order of magnitude larger than that in IMPATT diodes) behave in a somewhat different way. Shown in Fig. 3 are the typical reverse branches of a Zener diode *I—V* curves — before (curve *1*) and after (curves *2 — 4*) the ultrasonic treatment. One can see that three successive ultrasonic treatments result in the reverse current decrease by no more than an order of magnitude, while the near-avalanche part of the *I—V* curve remains practically the same. Holding Zener diodes in vacuum also leads to rather insignificant changes in their *I—V* curves, except for the leakage currents drop by a factor of 3 — 4. The latter fact indicates the effect of ultrasonic treatment and holding in vacuum on the p—n junction outcroppings.

The structural defects in the alloy p—n junction bulk manifest themselves in the microplasma breakdown. The first ultrasonic treatment somewhat changes the breakdown structure; the microplasma breakdown occurs at a voltage of about 0.1 eV lower than that in the initial sample. Subsequent ultrasonic treatments practically do not change the breakdown fine structure — see Fig.4.

To understand the above results, one should take into account the nature of structural defects in the alloy p—n junctions. These are the extended linear defects (dislocations) in the space-charge region of a

Effect of ultrasonic treatments on the parameters of Cr—n—n^+—Si Schottky diodes

Ultrasonic treatment	φ_B, V	n	$10^8 I_R$, A	V_B, V
Initial sample	0.62	1.20	20	150
1 V, 160 kHz, 1 h	0.62	1.20	10	150
2 V, 160 kHz, 1 h	0.62	1.15	9	150
5 V, 160 kHz, 1 h	0.62	1.15	9	150

Note. Reverse current I_R at a voltage $V = 2$ V.

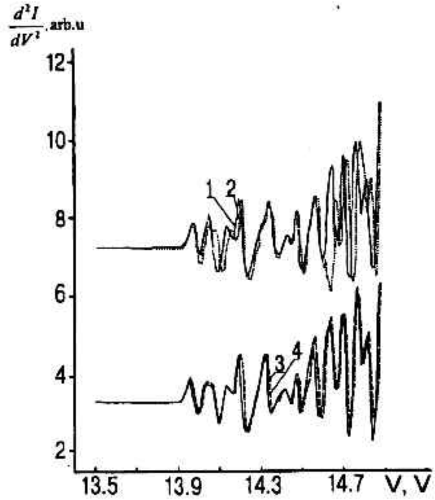

Fig.4. d^2I/dV^2 versus V curves for a silicon alloy Zener diode — initial (*1*) and after the ultrasonic treatments: *2* — 2 V, 160 kHz, 1 h; — the same as *2* plus 3 V, 160 kHz, 1 h; 4 — the same as *3* plus 5 V, 160 kHz, 1 h

Zener diode. Their mobility is low, so one can detect their movement in the semiconductor bulk only at temperatures about that of their generation (i.e., the temperatures at which the sample cooling begins [11]). But such temperatures are not produced during the ultrasound absorption by silicon.

Conclusion

The results obtained evidence that ultrasonic treatment at room temperature stimulates a number of processes in silicon diffusion IMPATT diodes and power Schottky diodes of small acting area, involving a modification of the impurity-defect structure [6, 12, 13], decomposition of defect complexes, defect diffusion and gettering, rearrangement and, in some cases, annihilation of dislocations, etc. This results in the charge transport mechanism changing from generation-recombination to the diffusion one, thus enabling the ideal Shockley diode realization in a silicon p—n junction.

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ВПЛИВ УЛЬТРАЗВУКОВОЇ ОБРОБКИ КРЕМНІЄВИХ ЛАВИННО-ПРОЛІТНИХ ДІОДІВ, СИЛОВИХ ДІОДІВ ШОТТКІ ТА СТАБІЛІТРОНІВ НА ЇХНІ ЕЛЕКТРИЧНІ ХАРАКТЕРИСТИКИ

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Р е з ю м е

Було проведено ультразвукову обробку корпусованих кремнієвих лавинно-пролітних діодів та силових діодів Шотткі. Вона суттєво зменшила зворотний струм діодів та підвищила стабільність вольт-амперних характеристик. Отримані результати свідчать про те, що ультразвукова обробка при кімнатній температурі викликала істотну перебудову домішково-дефектної структури p — n-переходів у досліджених діодах. Ідеальний діод Шоклі реалізується в кремнієвому p — n-переході внаслідок заміни генераційно-рекомбінаційного механізму струму на дифузійний. З метою порівняння було також досліджено кремнієві сплавні стабілітрони, піддані ультразвуковій обробці.

ВЛИЯНИЕ УЛЬТРАЗВУКОВОЙ ОБРАБОТКИ КРЕМНИЕВЫХ ЛАВИННО-ПРОЛЕТНЫХ ДИОДОВ, СИЛОВЫХ ДИОДОВ ШОТТКИ И СТАБИЛИТРОНОВ НА ИХ ЭЛЕКТРИЧЕСКИЕ ХАРАКТЕРИСТИКИ

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Р е з ю м е

Была проведена ультразвуковая обработка корпусированных кремниевых лавинно-пролетных диодов и силовых диодов Шоттки. Она заметно уменьшила обратный ток диодов и увеличила стабильность вольт-амперных характеристик. Полученные результаты свидетельствуют о том, что ультразвуковая обработка при комнатной температуре вызвала существенную перестройку примесно-дефектной структуры p — n-переходов в исследованных диодах. Идеальный диод Шокли реализуется в кремниевом p — n-переходе в результате замены генерационно-рекомбинационного механизма тока диффузионным. Для сравнения были также исследованы кремниевые сплавные стабилитроны, подвергнутые ультразвуковой обработке.