

**Y.R.Blyashko, L.N.Dusheva**

## **Low-barrier GaAs diodes for a microwave and millimeter wave equipment**

The manufacturing process and the GaAs low-barrier diode specifications are considered. The current transport mechanism for Au-Ge – GaAs Schottky diodes is determined. The dynamic characteristic analysis of a low-barrier detectors is carried out.

### **INTRODUCTION**

The basic tendency of radio electronics development always was mastering of more and more short-wave ranges of electromagnetic oscillations. The technical base of this process is the increase of operating frequencies of electronic devices. The latter is provided by both as an improvement of the design and manufacturing techniques already known, and as a creation of new devices which principles of operating in the best way correspond to peculiarities of the mastered range.

Especially pressing need for new ideas and principles of construction of electronic devices arises at transition from usual radio range in the range of ultrahigh frequencies covering a site of a spectrum of electromagnetic oscillations from 0.5 up to 3000 GHz, which length of waves (50 – 0.01 cm) are comparable with the sizes of devices and elements of a transmitting channel.

The serious achievement of last years is the manufacture of GaAs diodes with Schottky barrier which are used as frequency converters and detectors in a range from decimetre up to millimetre waves. Replacement Ge and Si with GaAs, and p-n-transition with a Schottky barrier allows to expand noticeably dynamic and frequency ranges of microwave oscillations detection.

Recently in manufacturing techniques of Schottky diodes we began to widely use an epitaxial growth that allows to minimize the  $R_s C_j$  product (where  $R_s$  - series resistance,  $C_j$  - capacity of a barrier layer) to increase limiting frequency. Losses of transformation [1] are connected with properties of a semi-conductor material as follows:

$$R_s \cdot C_j \approx d \cdot \varepsilon^{0.5} / N^{0.5} \cdot \mu \quad (1)$$

The purpose of the present work is the description of manufacturing techniques of diodes with the lowered height of a barrier and the investigations of their static and dynamic characteristics.

### **INVESTIGATION TECHNIQUES**

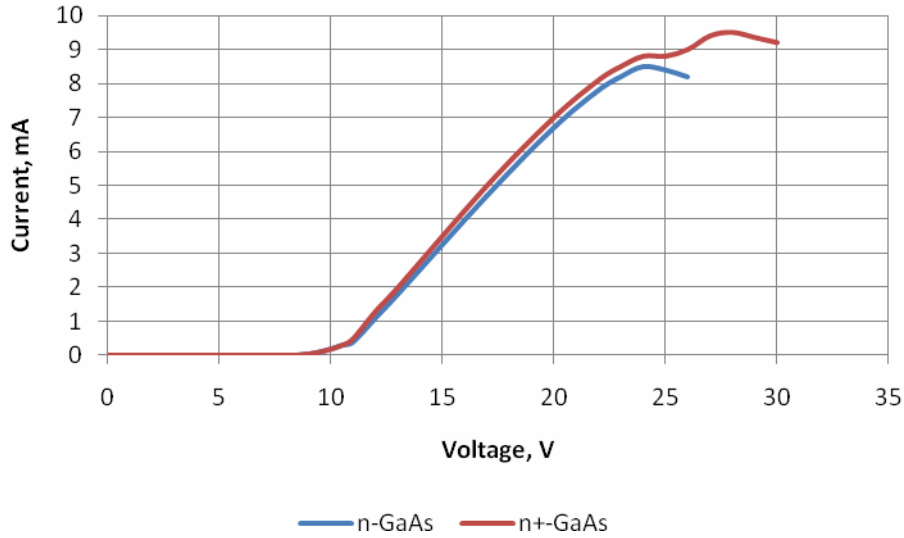
#### **1. The incoming inspection of semiconductor structures**

In the present work we use the incoming inspection of epitaxial structures parameters, based on the analysis I-V characteristics of two clamping probes located the surface of semiconductor structure [2]. The form of I-V characteristics of two probes is specific for two Schottky barriers included towards each other (Fig. 1).

Concentration of an doping impurity is defined by expression (2)

$$N = K \cdot U_{th}^{-1.33} \quad (2)$$

where  $K$  - the numerical factor, which size depends on type of the semiconductor, for GaAs  $K = 187,2$ ;  $N$  - normalized on  $10^{16} \text{ cm}^{-3}$ ;  $U_{th}$  - voltage of breakdown, V.



**Fig.1. I-V characteristics of two clamping probes**

Expression for thickness of a layer

$$d = \frac{I_s \cdot U_{th}^{1,33}}{2 \cdot \pi \cdot q \cdot v_s \cdot s \cdot k} \cdot \exp\left[\pi \cdot I \cdot \frac{U_s - U_{th}}{4,53 \cdot I_s \cdot U_{23}}\right] \quad (3)$$

and expression for mobility of the majority carriers of a charge

$$\mu = \frac{2 \cdot \pi \cdot I \cdot s \cdot v_s}{4,53 \cdot I_s \cdot U_{23}} \cdot \exp\left[-\pi \cdot I \cdot \frac{U_s - U_{th}}{4,53 \cdot I_s \cdot U_{23}}\right] \quad (4)$$

where  $U_{23}$  - potential difference between probes 2 and 3 at a current value between the probes, equal  $I$ ;  $U_s$ ,  $I_s$  - voltage and current of saturation I-V characteristics of two clamping probes;  $s \sim 1$  mm - distance between probes;  $v_s$  - saturation velocity of carriers in the semiconductor;  $q$  - electron charge;  $k$  - Boltzmann's constant.

## 2. The process of manufacturing of Schottky diodes

Unlike the earlier used process of electrochemical deposition of metal compositions [3] in the present work the method of vacuum thermal deposition of metals with the subsequent "lift-off" lithograph is applied. The choice of this method is justified by that the topological sizes and the form of the metallization precisely correspond to the used photo mask. It is important enough to obtain the calculated area of a barrier which defines the capacitance of the barrier and, hence, limited operating frequency of the diode.

An eutectic Ge-Au alloy which is used as the material of an ohmic contact vacuum thermal deposited on a semiconductor plate at a room temperature with thickness of 0.1-0.2  $\mu\text{m}$ . The layer of Au of 1-2  $\mu\text{m}$  is sequent deposited.

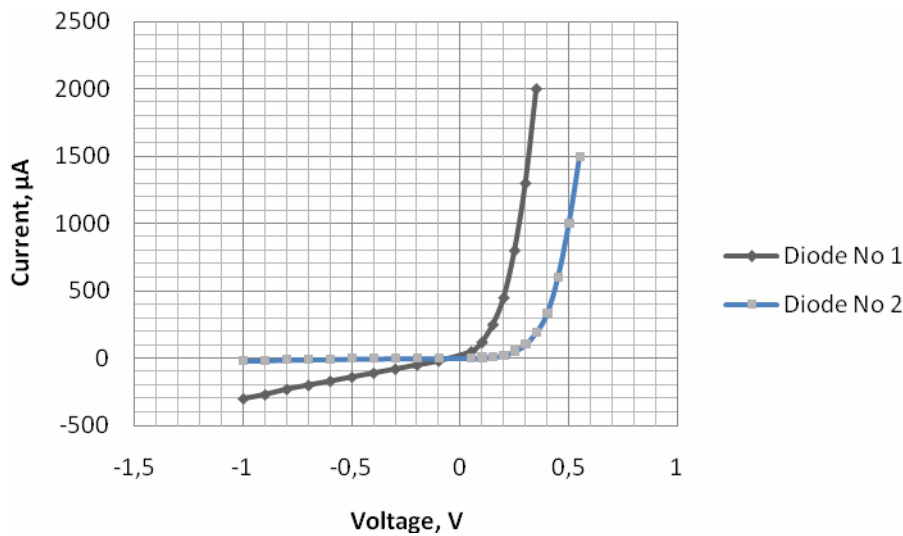
The formation of ohmic contact is made in a chamber with IR-heating in an air atmosphere. The temperature of process makes  $400 \pm 10$   $^{\circ}\text{C}$ . Time of heat treatment - 30-40 min. The minimal resultant resistance of the ohmic contact should not exceed  $10^{-5}$  ohm/cm<sup>2</sup>.

For formation of barrier contact the layers Ge-Au (thickness 0.03-0.05  $\mu\text{m}$ ) and Au (thickness 1-2  $\mu\text{m}$ ) are consistently deposited on n-GaAs surface. Heat treatment of a plate with the purpose to decrease the height of a barrier of the diode is performed in a similar manner to formation of an ohmic contact.

The polyimide film of 2-3  $\mu\text{m}$  thickness is put on a surface of a GaAs plate. The plate from a underside is etching up to the residual thickness of 8-10  $\mu\text{m}$  and by means of a photolithography the mesa-structure of the diode is formed.

As a result of all operations performed the matrix of diodes with beam leads with a base of a polyimide film is formed. The polyimide film thickness 2-3  $\mu\text{m}$  is elastic and strong enough to allow to make grading and transportation of a matrix of diodes without their damage.

The experimental I-V characteristics of two diodes with different height of a barrier are shown on Fig.2.



**Fig. 2. Experimental I-V characteristics of low-barrier diodes**

### 3 Static characteristics of low-barrier GaAs diodes with Schottky barrier

The first investigations of rectifying properties of metal-semiconductor contacts usually attribute to Brown who has in 1874 found out dependence of full resistance of contacts from polarity of the applied voltage and the peculiarities of their manufacture. The practical use of rectifying properties of point contact has began the 1904. In 1931 Wilson constructed the theory of a transport charge in the semiconductors, based on solid state zone theory. Subsequently this theory has been applied to metal-semiconductor contacts. In 1938 Schottky has come out with the assumption, that the potential barrier was created by a motionless spatial charge in the semiconductor, not due to an intermediate chemical layer between a metal and a semiconductor. Such a barrier is called Schottky barrier.

The potential barrier formed due to electric forces of the image blocks electron emission from metal. The decrease of this barrier in process of increase in the applied external electric field is called Schottky effect.

It is known [4], that a charge transfer through contact metal-semiconductor is carried out mainly by the majority carriers. There are four basic transport processes at direct displacement of contact Schottky:

1. Over barrier transfer prevailing in diodes Schottky on moderately doped semiconductors;
2. Electrons quantum-mechanical tunneling through a barrier at higher doping levels;

3. Recombination in the zone of a spatial charge;
4. Injection of holes from metal in to a semiconductor.

Over barrier electron transfer in semiconductors with high mobility can be completely described within the limits of the theory of thermionic emission. The density of a full current in this case equal to:

$$J1 = [A^* \cdot T^2 \cdot \exp(-\frac{q \cdot \varphi_{bn}}{k \cdot T})] \cdot [\exp(\frac{q \cdot V}{k \cdot T}) - 1] \quad (5)$$

where  $A^*/A=0.068$  for weak fields and 1.2 for strong fields for n-GaAs with orientation (100),  $A = 120 [A \cdot cm^{-2} \cdot K^{-2}]$  – Richardson's constant for free electrons;  $\varphi_{bn}$  - height of a barrier.

The diffusion theory gives following expression for density of a current through a barrier

$$J2 = \{ [\frac{q^2 \cdot D_n \cdot N_C}{k \cdot T} \cdot [\frac{q \cdot (V_{bi} - V) \cdot N_D}{\epsilon_s}]^{0.5}] \cdot \exp(-\frac{q \cdot \varphi_{bn}}{k \cdot T}) \} \cdot [\exp(\frac{q \cdot V}{k \cdot T}) - 1] \quad (6)$$

If electrons transport follows the termoemission-diffusion theory the expression for I-V characteristics has the form:

$$J3 = [A^{**} \cdot T^2 \cdot \exp(-\frac{q \cdot \varphi_{bn}}{k \cdot T})] \cdot [\exp(\frac{q \cdot V}{k \cdot T}) - 1] \quad (7)$$

In devices on heavily doped semiconductors a prevailing process of carry of a charge appears to be tunneling. In this case the density of a current can be written down in the form of

$$J4 = J_s \cdot [\exp(\frac{q \cdot V}{n \cdot k \cdot T}) - 1] \quad (8)$$

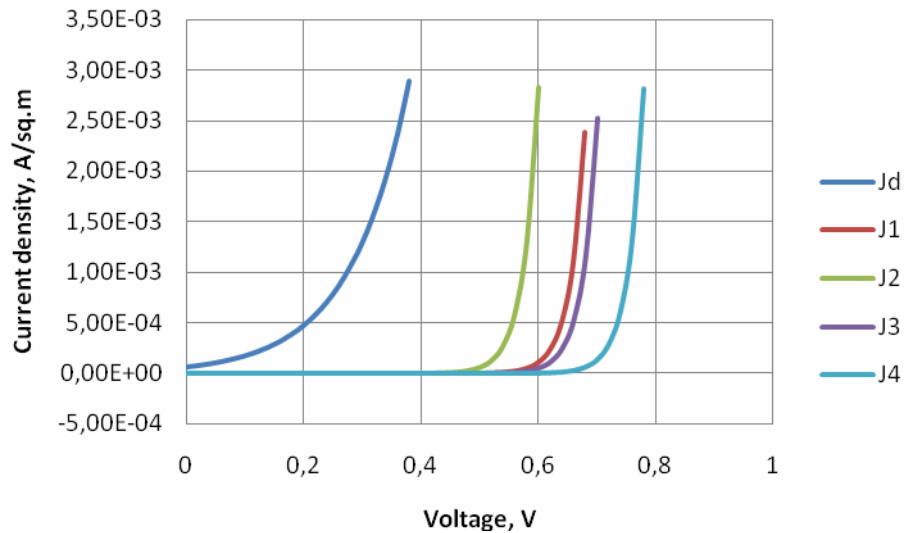
where n – ideality factor.

The I-V characteristics of Schottky diodes on GaAs, calculated for different mechanisms of a current passages and obtained experimentally are shown on Fig. 3.

The I-V characteristic of the low-barrier diode on GaAs can be described by the follows expression

$$Jd = [B \cdot A^{**} \cdot T^2 \cdot \exp(-\frac{q \cdot \varphi_{bn}}{k \cdot T})] \cdot [\exp(\frac{q \cdot V}{k \cdot T}) - 1] \quad (9)$$

where  $B = 2 \cdot 10^4$  - factor of increase in a current density at a decrease of a height of a barrier.



**Fig.3. I-V characteristics of low-barrier diodes in comparison with usual diodes**

#### **4 Dynamic characteristics of detectors on GaAs low-barrier diodes**

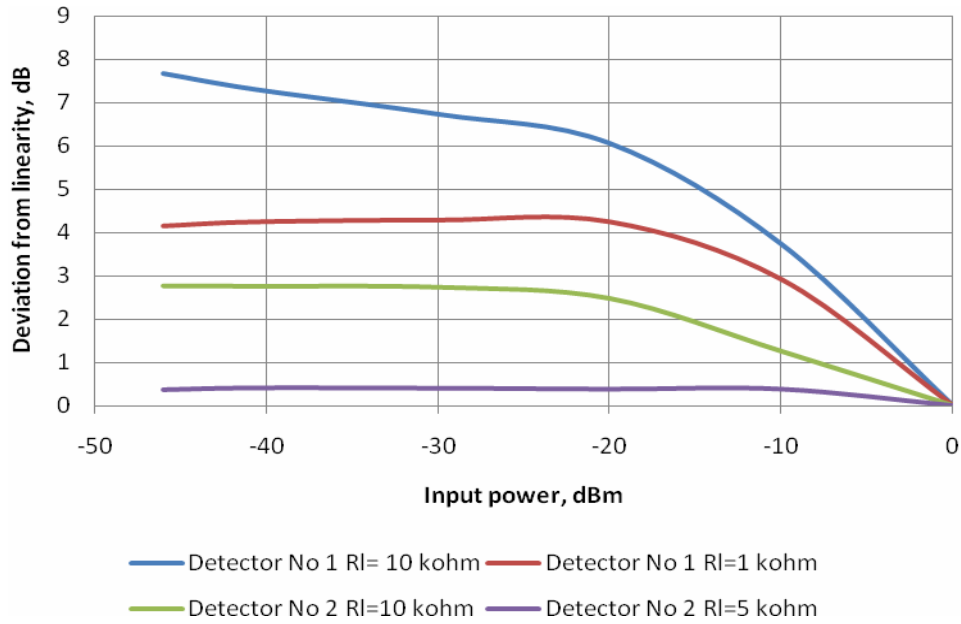
On the base of the described above low-barrier diodes the complete set of coaxial detectors in 0,01 - 26,5 GHz range and waveguide detectors in 18 - 178 GHz range with subranges in accordance with the standard waveguide sections was developed.

In [5] attempt is undertaken to present the detector specifications in such that the designer of radio equipment has the opportunity to obtain optimum requirements to the detector. So, for example, it is possible to expand a dynamic range of square-law detecting by selection of resistance of loading of the detector with loss of its sensitivity or the same aim can be reached by a choice of other type of the diode with smaller loss of sensitivity.

The opportunity of wider optimization of detectors specifications appears due to application of low-barrier diodes which manufacturing techniques allows to vary the height of a barrier within 0.1 - 0,7 eV.

The methods of controllable decrease of a height of a barrier of a diode allows to optimize the I-V characteristic of the diode in such a manner that at preservation of high sensitivity and loading ability of the diode it is possible to expand a dynamic range of square-law detecting in higher levels of input power range.

Fig. 4 shows deviations from linearity of detectors of type 1 and 2 (Fig.2). From the figure one can see that in the detector of the first type the standard range of square-law detecting (-20 dBm) is reached only at 1 k $\Omega$  load and at 50  $\Omega$  load it is possible to expand it up to -10 dBm. In the detector of the second type the standard range of square-law detection is reached already at 10 k $\Omega$  load and there is an opportunity to optimize loading (~5 k $\Omega$ ) for expansion of a range of square-law detecting up to 0 dBm and above.



**Fig.4. A deviation from the linearity of low-barrier detectors**

The deviation from square-law detecting of the detector was defined in accordance with the following formula:

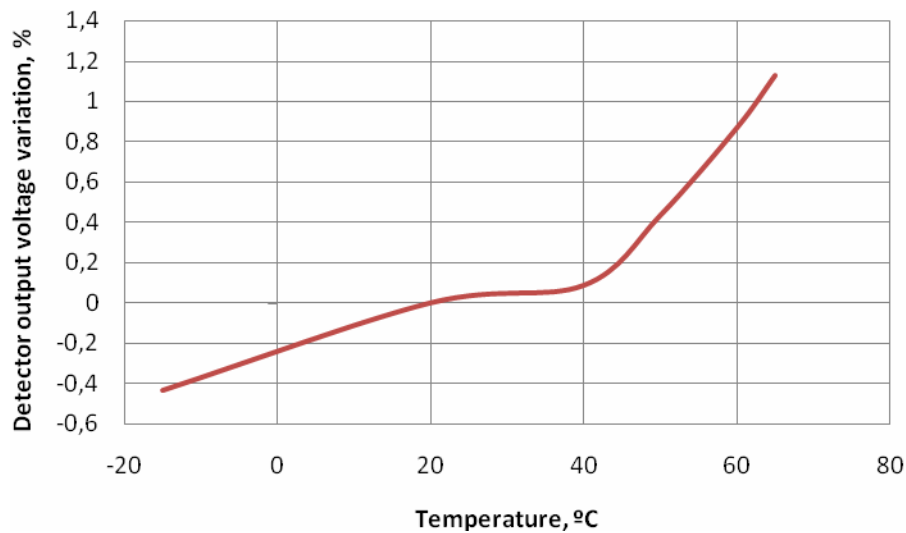
$$\delta U = 10 \cdot \log\left(\frac{U_i}{U_0}\right) - P_{in} \quad (10)$$

where  $U_i$  - dynamic output voltage of a detector, V;

$U_0$  - output voltage of a detector at  $P_{in} = 0$  dBm, V;

$P_{in}$  - input power, dBm.

Diodes are made of n-GaAs and use the majority carriers, the concentration and mobility of which are great enough to provide low temperature dependence I-V characteristics. Fig.5 shows temperature dependence of the output voltage of the detector.



**Fig.5. Temperature dependence on a detector output voltage**

## RESULTS AND DISCUSSION

In process of controllable decrease of a height of a barrier of Au-Ge contact considered here - GaAs heat treatment is a key.

In [6] influence of heat treatment on behavior of Au-GaAs structures was investigated. The results of these investigations at temperatures above 350 °C show intensive migration of Ga in Au up to a limit of solubility with the subsequent fast increase in concentration of Ga at eutectic Au-GaAs temperature of 450 °C. At this temperature the intensive migration of Au to GaAs takes place. It remains rather stable up to 450 °C, but at 500 °C Ga rapidly diffund into Au. Diffusion of Ga in Au is accompanied by formation of vacancies of Ga in GaAs. Above 400 °C the significant degradation of I-V characteristics of Au-GaAs contacts occurs which before heat treatment had almost ideal straightening of a contact to a height of a barrier 0,9 eV. The effect of heat treatment is accompanied by the increase in density of a current and ideality factor, that confirms the mechanism of thermoelectronic-field emission. It would be possible to explain it substantial growth of density of donors regarding the depletion region of immediately adjacent to a metal, however both vacancies of Ga, and atoms of Au in GaAs behave as acceptors. (be possible, however, that Au in GaAs can be both an acceptor, and a donor).

Moroney and Anand [7] shown, that Schottky diodes from alloy Au-Ge on n-GaAs yield high results at their use as mixers and detectors. Such diodes have a low potential barrier (0,27 - 0,9 V) at temperatures of manufacturing 300 - 25 °C, accordingly. Contact of an Au-Ge alloy with low doped n-GaAs generated at 500 °C is an ohmic. It can be given a following explanation. During heat treatment Ga vacancies which subsequently are filled with Ge atoms, are formed by becoming donors. If the resultant potential barrier is low it is possible to consider, that on a surface there is a thin layer of a degenerated material ( $10^{-3}$  μm) which changes the form of a barrier. Then to transport the majority carriers jump above the first part of a barrier due to thermionic emission a small direct displacement is required and other part of the barrier is thin enough to tunnel carriers.

We way imagine the following mechanism of interaction of components of Au-Ge - GaAs system is as a duration heat treatment. Diffusion process is defined by temperature and time. Besides in this case it occurs from the limited source what the thin film of Au-Ge alloy is. Temperature (400 °C) and time (30 sec) at heat treatment of barrier contact are the same, as at heat treatment of ohmic contact of the same composition. Only a thickness of a film of an alloy differs. If at drawing a film of an alloy its thickness has appeared too small, the decrease of a barrier does not occur even at the increase of temperature and time of heat treatment. The increase in thickness of a film of an alloy above optimum at standard heat treatment leads to full degradation of a barrier. Atop of a film of an Au alloy layer for a thickening of a metallization of the diode output. Hence, the limited source of diffusion is only for Ge. Au atoms, intruding into GaAs lattice, stimulate process of diffusion of Ge atoms which in interstices become donors. The thin layer obtained as a result of heat treatment degenerated the semiconductor changes the height of a barrier.

## CONCLUSION

The developed process of controllable decrease of a height of a barrier of Au-Ge - GaAs contacts allows to manufacture high-frequency low-barrier detector diodes with the requirements for application in a microwave and millimetre wave equipment both as power detectors and for the special purposes. Detectors are used in signal generators and frequency synthesizers in APC system, in panoramic measurements, in receiving devices for LF envelope enhancement, in pulse measurements.

The current density and ideality factor increase at heat treatment justified the mechanism of thermoelectronic-field emission in Au-Ge - GaAs contacts

## References

1. **И.Ананд, В.Морони.** Смесительные и детекторные СВЧ-диоды. Полупроводниковые приборы СВЧ. Под редакцией Ф. Брэнда. М.: Мир, 1972. С.60.
2. **В.Н.Анощенков, В.В.Артамонов, Ю.Р.Бляшко.** Применение автоматизированной аппаратуры для входного и межоперационного контроля технологии изготовления БИС. Тез. докл. Всесоюзн. конф. "Средства измерений, диагностики и контроля РЭА IV-V поколений", Горький, 1986 г.
3. **F.Lewen, D.G.Paveliev, B.Vowinkel, J.Freyer, H.Grothe and G.Winnewisser,** "Planar Schottky Diodes for THz Application", Proceedings 4<sup>th</sup> Int. Workshop on Terahertz Electronics, Erlangen Germany, Sep. 5-6, 1996.
4. **С.М.Зи.** Физика полупроводниковых приборов. 1984, М., «Мир». Т.1. С.266.
5. **Ю.Р.Бляшко, Л.Н.Душева, Т.И.Петрова.** Низкобарьерные широкополосные детекторы. Петербургский журнал электроники, 2001 г., № 3, с. 52-56.
6. **Madams C.J., Morgan D.V., and Howes M.J.:** "Outmigration of gallium from Au-GaAs interfaces", Electron Lett., 1975, 11, (24), pp.574-575.
7. **W.J.Moroney, Y.Anand.** "Low barrier height gallium arsenid microwave Schottky diodes using gold-germanium alloy", in 1970 Proc. Third Int. Symp. Gallium Arsenide.