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OHMIC CONTACTS TO III-V COMPOUND SEMICONDUCTORS: A REVIEW OF FABRICATION TECHNIQUES

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Abstract—After a brief introduction on the phenomena governing the ohmic contact formation and measurements in metal—semiconductor structures, we present a review of papers on the ohmic contact realization onto III-V compounds. We discuss the thermal behaviour of various multicomponent metal—semiconductor systems (alloying, sintering, use of lasers and electron beams) and comment about overdoping the semiconductor surface before metal deposition (diffusion, ion implantation, epitaxy). We show that, in a general way, the metal III-V semiconductor interactions lead to the formation of compounds. From an electrical point of view, it seems that the main consequence of the compounds appearance is not a large change of the barrier height due to a change of the interface chemistry but the rough interface resulting from particle precipitation. We conclude that, if contacts made up to now, are often simple and usable, they are still far from ideal.

NOTATION

TE	thermoionic emission
TFE	thermoionic field emission
FE	field emission
r_c (Ω cm^2)	specific contact resistance
R_C(Ω)	contact resistance
ϕ_B (eV)	barrier height
A	Richardson constant
E_{00}	tunneling parameter
m^*	effective mass of tunneling carriers in the semiconductor
ϵ	semiconductor permittivity
$N_{D,A}$	dopant concentration
q	electronic charge
$\hbar$	Planck's constant
d	contact diameter
s	contact separation
S	contact area
w	thickness of semiconductor wafer
R_B	spreading resistance
ρ_B	resistivity of semiconductor
IC	integrated circuit
PEBA	pulse electron beam annealing
RT	room temperature
SIMS	secondary ion mass spectroscopy
LED	light emitting diode
FET	field effect transistor
MESFET	metal semiconductor field effect transistor
IMPATT diode	impact-avalanche transit-time diode
DH	double heterostructure
LPE	liquid phase epitaxy
VPE	Vapour phase epitaxy
MBE	molecular beam epitaxy
RBS	Rutherford backscattering

1. INTRODUCTION

Although metal—semiconductor ohmic contacts have generated much less scientific interest than other interfaces, their practical importance is evident. All semiconductor devices need at least one ohmic contact and often the quality of ohmic contact is one of the most significant factors affecting the performance of III-V semiconductor devices.

The term "ohmic" refers in principle to a contact which is noninjecting and has a linear I-V characteristic in both directions. In practice a contact is considered ohmic if the voltage drop across it is much smaller than that across the device. The linearity of the I-V relationship is less important provided the contact resistance is very small compared with the device resistance. Other important features of ohmic contacts in semiconductors devices are their reliability and reproductibility. In particular the contact material should not undergo electromigration under high electric fields nor modify the active structure characteristics during device operation. It is often required that the thermal impedance of the contact should be low to remove heat from the device.

III-V compound semiconductors are generally much more likely to be damaged during device processing than the elemental semiconductors; the problems which still have to be resolved in ohmic—contact technology confirm this statement. Thermal instability and surface dissociation at relatively low temperatures are the main difficulties during contact formation. The reactions between contact material and semiconductor elements, if not controlled, result in contact degradation with time. Although many problems in ohmic contact technology have not yet been overcome, noticeable progress has been made during the past few years.

Many papers on ohmic contacts to III-V compound semiconductors have been published. The most comprehensive paper is that by Rideout[1] who gave an excellent theoretical treatment and discussed the techniques used some six to seven years ago. Much information about ohmic contacts can be found in books by Milnes and Feucht[2], and Schwartz[3].

The aim of this paper is to present the various approaches investigated recently and to review the fabrication techniques of ohmic contact formation to III-V compound semiconductors.

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2. METAL—SEMICONDUCTOR PHENOMENA RELATED TO OHMIC CONTACT FORMATION

2.1 *Theoretical background*

A comprehensive analysis of fundamental contact phenomena in metal—semiconductor contacts is given in[2, 4, 5]. In this paper, we shall restrict ourself to a short presentation of the mechanism of current transport and discuss the important aspects of ohmic contact technology.

Experimental studies of metal—semiconductor contacts have shown that most of the metal—semiconductor combinations form depletion layer contacts (usually rectifying or blocking). The conduction properties of such contacts are determined by the actual transport mechanism which can be due to:

(1) Thermionic Emission (TE) of carriers over the top of a barrier (which give rise to current rectification);

(2) Thermionic Field Emission (TFE), i.e. the tunneling of hot carriers through the top of the barrier (when high doping levels narrow the depletion layer);

(3) Field Emission (FE), i.e. carrier tunneling through the whole barrier, which is the preferred mode of current transport in ohmic contacts;

(4) Recombination in the space—charge or in the neutral regions.

The dominant mechanism of current flow depends primarily on temperature, barrier height, doping concentration profile, charge carriers effective mass and dielectric constant. Besides, several other factors such as the presence of interfacial layers or the stoichiometry of the semiconductor surface, influence the transport mechanism.

The electrical properties of ohmic contacts are characterized by their specific resistance $r_c[\Omega\,\mathrm{cm}^2]$ defined as

$$r_c = \left(\frac{\partial I}{\partial V}\right)^{-1}_{V=0} \qquad (1)$$

or

$$r_c = \lim_{\Delta S \to 0} R_c \Delta S \qquad (2)$$

where R_c is the total contact resistance, S is the contact area. Theoretical expressions for specific contact resistance were given by Yu[6]. Taking the theoretical I–V characteristics in the thermionic emission, thermionic-field emission and field emission regions he has shown that r_c is determined predominantly by the following factors:

$$\exp\frac{\phi_B}{E_{00}} \quad \text{for } FE \qquad (3)$$

$$\exp\left[\frac{\phi_B}{E_{00}\coth\left(\frac{E_{00}}{\mathrm{kT}}\right)}\right] \text{for TFE} \qquad (4)$$

$$\exp\frac{\phi_B}{\mathrm{kT}} \quad \text{for TE} \qquad (5)$$

where ϕ_B is the barrier height, and E_{00} the tunneling parameter defined by

$$E_{00} = \frac{q\hbar}{2}\sqrt{\left(\frac{N_{D,A}}{m^*\epsilon}\right)} \qquad (6)$$

where m^* is the effective mass of tunneling carriers in the semiconductor, ϵ its permittivity, $N_{D,A}$ the dopant concentration, q the electronic charge, $\hbar$ the Planck constant. E_{00} is a very useful parameter in predicting the blocking or ohmic characteristics of a metal—semiconductor contact. For $\mathrm{kT}/E_{00} \gg 1$ the thermionic process dominates and the contact behaves as a Schottky barrier. For $\mathrm{kT}/E_{00} \ll 1$ field emission dominates and the contact exhibits ohmic characteristics. In the range where $\mathrm{kT}/E_{00} \approx 1$ a mixed mode of transport occurs.

The functional dependence of the specific contact resistance on semi-conductor doping level and barrier height is shown in Fig. 1. In the FE region (highly doped semiconductor, for instance $> 5 \times 10^{17}$ e/cm^3 for n-type GaAs) log r_c depends linearly on $(N_{D.A})^{1/2}$ with slope $(2\sqrt{(m^*\epsilon)}/q\hbar)\phi_B$. In the TE range (low doping i.e. $< 10^{16}$ e/cm^3) r_c is equal to $(k/qAT)\exp(\phi_B/\mathrm{kT})$ and independant on doping level. The TFE regime bridges the two. TFE and TE are temperature dependent (r_c decreases with increasing temperature), while FE is temperature independent.

With regard to current transport mechanisms and the expressions for specific contact resistance, it is obvious that there are several possible ways for achieving ohmic contact. One consists of having a layer of very heavily doped semiconductor immediately adjacent to the metal. In such a case the depletion region in the semiconductor become so thin that even in a high barrier, field emission dominates and the contact is ohmic. This is the most commonly used approach and will be discussed later.

The second approach consists of having a negligible potential barrier at the metal—semiconductor interface. In the case of III-V compound semiconductors, however, the barrier height is essentially independent of the metal used and is determined by interface states originating from surface states[7, 8], from metal-induced gap states[9, 10], or from interface chemical reactions

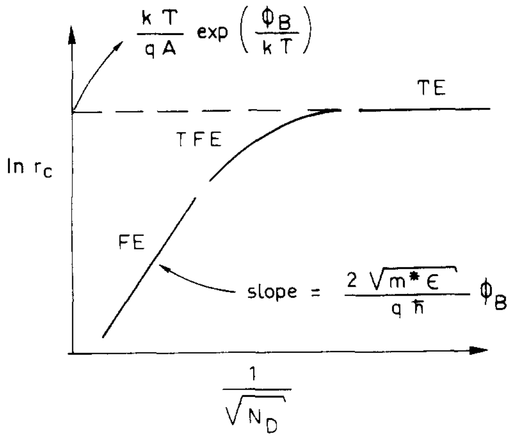

Fig. 1. Theoretical dependence of the specific contact resistance on semiconductor doping level and barrier height, after [6].

between metal and semiconductor[11-13]. Then, the reduction of barrier height cannot be obtained by the metal choice but rather by the introduction of impurities on the semiconductor surface to introduce surface states for Fermi level pinning. This possiblity has been verified by Massies *et al.*[14] who saturated the GaAs surface with H_2S (sulfur is a shallow donor in GaAs) before epitaxial deposition of the metal. The barrier height was reduced from 0.8 to 0.4 eV and, for a semiconductor doping of $n \simeq 10^{18}\,\mathrm{cm}^{-3}$, Al/$n$-GaAs ohmic contacts with a specific contact resistance of $r_c \approx 10^{-4}\,\Omega\,\mathrm{cm}^2$ were realized. The main difficulty of the method is the required perfect control of the semiconductor surface.

Another method which may be used to form an ohmic contact is the introduction of recombination centres near the metal—semiconductor interface (e.g. by damaging or straining the semiconductor surface). If the density of these centers is high enough, recombination in the depletion region will become the dominant conduction mechanism and will cause a significant decrease of contact resistance. This approach has been applied sometimes to obtain ohmic contact to Ge surfaces (sand-blasted or Ge bombarded), but since a defect or a strained region can also getter impurities and/or can generate underlaying point defects, this method is not very promising. On the contrary, the present consensus is that any damage of the semiconductor subsurface must be avoided in order to assure the long term stability of the devices[15].

2.2 *Contact resistance measurements*

Several methods have been used to evaluate the specific resistance of metal—semiconductor ohmic contacts[16-27]. We shortly present two of them just to point out problems arisen in practice by measurements of r_c.

In general, the main difficulty consists in the separation of total resistance measured between two contacts into contact, spreading (the term due to nonlinearity of the electric field around the contact) and residual (due to semiconductor and probes) resistances. The method of Cox and Strack[21] makes use of the dependence of total measured resistance on ohmic contact areas. In its original version the technique utilizes contacts on front and back of planar samples (circular contacts of different diameters on top, and large area back side contact common to all measured contacts). The contact resistance is obtained by curve fitting method plotting the measured resistance as a function of the ratio of wafer thickness to dot diameter when the resistivity of the semiconductor is known. The modification proposed by Keramidas[22] applies the procedure of Cox and Strack to measurements made between adjacent contacts placed on the surface of planar sample; it has the advantage that requires only one metallization process and can be used on thin layers. The tested structure is the multidot pattern of circular contacts with different diameter; the contacts are separated by the same distance irrespective of dot diameter. This allows the evaluation of contact resistance by sequential measurement of the resistance between dots separated by multiples of the near-neighbour contact distance. The results of such measurements give a family of curves $R = f(s, d)$, where s is the contact separation, d the contact diameter. The contribution of underlaying semiconductor material is eliminated by extrapolation of the straight lines $R(s)$ to zero, that of probe resistance by independent measurements. After substracting the spreading resistance the specific contact resistance is determined by plotting the results against $1/d^2$ and determining the slope of such line.

Another method of evaluating the specific contact resistance is the four probes procedure[25-27] shown in Fig. 2. The tested structure consists of four identical, equidistant circular contacts arranged on a straight line in such a manner that $d \ll s$ and $w \ll s$; d is the contact diameter, s the spacing between the contacts, w is the thickness of semiconductor wafer. The evaluation of specific contact resistance is obtained by measuring the voltage between the probe b–c, when the current is applied successively between the probes b–d and a–d. In the original version[25], the method neglected the spreading resistance; following the analysis given in[24-27] one can find that:

$$r_c = S(R_M - R_B - R_S) = S\left(\frac{V'_{bc}}{\dot{I}_{bd}} - \frac{V_{bc}}{\dot{I}_{ad}} F_1 - \frac{r_c}{S} F_2\right)$$

$$F_1 = \frac{\ln[4(s/d) - 1]}{2\ln 2}$$

$$F_2 = \frac{\Sigma y^m/2^{2m}(m!)^2}{\Sigma y^m/(m+1)(m!)^2 2^{2m}} - 1$$

$$y = \frac{\rho_B d^2}{4 r_c w}$$

where S is the contact area, R_M the measured resistance, R_B is the semiconductor resistance between the contacts, R_S the spreading resistance, ρ_B the resistivity of semiconductor, V'_{bc}, V_{bc} are the voltages between the points b–c, when the current is applied between b–d and a–d respectively, F_1 is a factor that allows for potential distribution in the surface layer, F_2 is a correction factor due to spreading resistance.

However, for r_c values lower than $10^{-6}\,\Omega\,\mathrm{cm}^2$, all experimental techniques are quite inaccurate because the square resistivity of the metal layer is in the same order of magnitude.

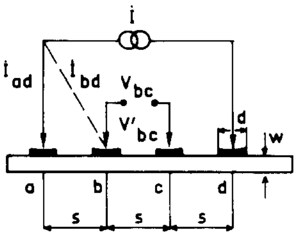

Fig. 2. Four-point method for measuring the contact resistance.

3. OHMIC CONTACT FABRICATION TECHNIQUES

All methods used in practice for ohmic contact fabrication rely on formation of tunneling metal—semiconductor junction by creating a thin heavily doped semiconductor layer at the interface. This highly doped semiconductor layer is formed either before the metal deposition (via diffusion, ion implantation or epitaxy) or during the contact preparation. The latter, the most widely used procedure, consists of depositing a multicomponent metal structure on the semiconductor surface and of heating the system. The metal layers usually contain a suitable dopant and the heat treatment is used to drive the dopant into the semiconductor to form the n^{++} or p^{++} layers. Tunneling junction metal—semiconductor is formed either via alloy regrowth, if a liquid phase is formed during heat treatment or by sintering. The properties of the contacts depend considerably on the choice of metallic layers, their thickness, the metal deposition conditions, the surface preparation and heat treatment procedures.

Metallic contact layers are usually prepared by vacuum deposition (electron beam or thermal evaporation, more rarely by sputtering). Alternatively, several plating techniques (such as electroplating, pulse plating or electroless plating) can be used. The most commonly used method of heat treatment of metal—semiconductor system is furnace alloying in H_2, or N_2, or N_2+H_2 flowing gas.

Since the III-V semiconductors are unstable under heat treatment[28–29], the loss of volatile components such as As and P might be expected during contact formation. In fact, the effect of release and evaporation of volatile component during the heating cycle has been experimentally verified for gold, and for gold- and silver-based contacts to GaAs, GaAlP, and GaP[30–33]. Several solutions have been tried to overcome this phenomenon. The problem may be partly avoided by using a very short alloying time. As an alternative method the use of arsenic overpressure has been proposed[34, 35] (Sebestyen *et al.*[32, 36] reported that the addition of gallium to the contact metal is useful). In the already developed method of thin phase epitaxy both components of the III-V semiconductor are supplied to contact materials—the non-volatile component by evaporation prior to alloying, the volatile component during alloying (either from the atmosphere or by molecular beam)[32, 35, 36].

3.1 *Ohmic contact formation by means of annealing of multicomponent metal-semiconductor systems*

3.1.1 *Alloy regrowth.* In current understanding the term "alloy regrowth" means the growth of a highly doped semiconductor region at the metal—semiconductor interface by means of a dissolution—segregation process. It is believed that during heating one or several contact components are molten and some of the semiconductor is dissolved in the melt. On cooling the dopant segregates from the melt together with the solidifying semiconductor. In reality, the alloying process is much more complex and will be discussed later.

Gold or silver are usually used as the base metal in alloyed contacts. Gold alloys are preferred to silver ones because silver reacts readily with the atmosphere (oxygen and sulfur) and to avoid aging effects, silver contacts should be hermetically sealed or covered with a suitable metal layer immediately after alloying.

Various elements are introduced into contact systems as doping species. Zn and Be, sometimes Mg, are usually chosen as acceptors for contacts to p-type semiconductors. Since Au–Zn evaporation and alloying process are not easily controllable (owing to the great difference of the Au and Zn vapor pressures and the poor adsorption of Zn on semiconductor surfaces) difficulties are often experienced in contacts prepared by conventional evaporation from Au–Zn alloy sources. As an alternative, in order to overcome these problems, Au–Zn contacts can be prepared by electroplating[37], sputtering[38] or the deposition by evaporation of multilayers Au/Zn/Au[39, 40]. Unlike Zn, beryllium has a vapour pressure close to that of Au so that the two metals can be evaporated almost congruently from Be–Au alloy sources. The main disadvantage of Be is its toxicity. Alloyed ohmic contacts with $r_c = 1.9\times10^{-5}\,\Omega\,\mathrm{cm}^2$ were obtained for p-GaAs ($N_A = 2\times10^{17}\,\mathrm{cm}^{-3}$) [53], $r_c = 8\times10^{-5}\,\Omega\,\mathrm{cm}^2$ ($N_A = 8.10^{18}\,\mathrm{cm}^{-3}$) [62] and $r_c = 1.1\times10^{-4}\,\Omega\,\mathrm{cm}^2$ ($N_A = 9\times10^{17}\,\mathrm{cm}^{-3}$) [26] were achieved for p-InP. For other III–V compound semiconductors typical values specific contact resistance are of the order $10^{-5}-10^{-4}\,\Omega\,\mathrm{cm}^2$. For the n-type material Te, Se, Si, Ge and Sn can be used as donors in contact systems. Since both Te and Se are highly volatile they are hardly used for contacts prepared by evaporation and alloying. The amphoteric impurities are easily deposited and besides, owing to their very low diffusion constant in III–V semiconductors they seem to be potentially most stable, reliable and reproducible for n^+ doping. The best alloyed ohmic contacts to n-GaAs were obtained with AuGeNi system; the specific contact resistance $r_c = 1.5\times10^{-6}\,\Omega\,\mathrm{cm}^2$ for $N_D = 5\times10^{16}\,\mathrm{cm}^{-3}$ was achieved[42]. For AuGeNi contacts to n-InP, $r_c = 8\times10^{-7}\,\Omega\,\mathrm{cm}^2$ ($N_D = 10^{17}\,\mathrm{cm}^{-3}$)[56].

A summary of experimental results on alloyed ohmic contacts will be presented in paragraph 3.1.4.

As mentioned above, the metallurgical interactions at the metal—semiconductor interface during alloying are far from well understood. It should be emphasized that the compositional analyses of these structures require significantly higher than 1 μm lateral resolution and only recently such investigations could be undertaken.

As an example, we can take the AuGeNi contact to n-GaAs. This is the most extensively investigated contact system and the most widely used ohmic contact in the production of various GaAs devices. For contact fabrication, Au and Ge are either coevaporated or deposited in separate films, with an overall composition corresponding to the eutectic, 12 wt% Ge. Ni is usually deposited as a top layer; sometimes an additional thin Ni layer (50 Å) is deposited on the GaAs surface prior to Au–Ge/Ni structure. The alloying is performed by heating the sample in a reducing atmosphere to a temperature between 420–550°C for times ranging from 15 s to 5 min.

Fast heating and cooling procedures are used to realize low resistivity contacts.

Several models have been successively proposed to illustrate the metallurgical behaviour of alloyed AuGeNi/*n*-GaAs contact. Through the use of microprobe Auger spectrometry and with bevelling technique together with X-ray diffraction analysis, the most accurate model in our mind was elaborated[63]. That model is shown in Fig. 3. At the early stage of reaction (300°C), Ge diffuses rapidly toward the contact surface. This is in agreement with the results[64, 65] showing that Ni is a sink for Ge. At the same time GaAs is decomposed at the interface mainly through the reaction between Au and GaAs, and partly through the reaction between Ni and GaAs: $Au + GaAs \rightarrow AuGa + As$, $Ni + As \rightarrow NiAs$. At this stage, hexagonal NiAs, and both polycrystalline β-AuGa and α'-AuGa are formed. At 400°C, Ge trapped in the surface layer diffuses inward. One part of the Ge is captured by NiAs and the other part reaches the substrate interface. At this temperature Ge starts to dope the GaAs. The rapid heating procedure is necessary to reduce the irregular penetration of Ni into the GaAs substrate. Contact anneal at 500°C produces a microscopic grain structure consisting of Ni–As–Ge and Au–Ga grains.

Since all components of the AuGeNi system play an active role in ohmic contact formation and performance, the proportion of the metallic layers are of primary importance. Ge is used as an n^+ dopant and acts as a donor in GaAs when it occupies Ga sites. Since Au acts as a selective getter for the Ga[15, 66–69], the amount of gold is very important for providing sites for Ge, but when Au is present in too high quantities (i.e. higher than the Ge atoms available to replace the gettered Ga) the non-stoichiometric conditions below the interface form a region of high resistivity and degrade the ohmic contact properties. Moreover during the contact formation the Au amount influences the amount of GaAs consumed. Ni plays a role of catalyser for the reaction between the GaAs and Au and provides the driving force for Ge diffusion. The amount of Ni influences both the morphology and the electrical properties as well as the contact reliability. Investigations of the LPE growth of GaAs from Au–Ge–Ni melt[42] have shown that an increase of Ni content in the melt increases the GaAs solubility and that concentrations of Ni above 2.67 wt% caused nonhomogeneous island type growth of GaAs. Consequently the thinnest possible Ni overlayer is suggested and a 200 Å Ni/300 Å Au–Ge structure is reported as an optimum. The results of Ohata and Ogawa[70] and Mackey[41] have shown that the contact structure can change during the aging (or further device processing) depending on Ni overlayer thickness. The observed increase on nonuniformity and Ni–As–Ge phase in the case of thick Ni layers was attributed to further growth of NiAs compounds. This growth was possible because of the partly unreacted Ni and was not observed with thin Ni layers where probably all Ni was consumed during the contact alloying. Mackey[41] has found that the critical value for the Ni layer is 50% of the Au–Ge layer thickness (typically 500 Å Ni/1500 Å Au–Ge is used). Ogawa[63] defines the optimum Ni thickness as lower than that of Au–Ge (1200 Å Ni/1400 Å Au–Ge was used). In practice, every laboratory has its own optimum technology which can differ from others. As a matter of fact, the technology of alloyed contacts is still weakly controllable.

3.1.2 *Sintering.* Sintering relies on the formation of ohmic contacts by solid phase reaction at the metal-semiconductor interface.

Sintered ohmic contacts such as PtSi are commonly used in Si IC where the formation of stable compounds offers the advantage of increased stability, reliability and reproducibility. Sintering has been applied to obtain Pd/Ge, Ni/Ge, Ta/Ge and Mo/Ge ohmic contacts to *n*-GaAs. The obtained results are summarized in Table 1. It is worth noticing that although neither element alone form ohmic contact to GaAs, they produce ohmic behaviour when used together in association.

Sinha *et al.*[71] reported ohmic behaviour in Pd/Ge/*n*-GaAs structure sintered at temperatures between 350 and 500°C. X-ray diffraction studies revealed the presence of PdGe, PdGa and $PdAs_2$ in sintered contacts. Ohmic behaviour was attributed to a combination of the doping action of Ge and the fast indiffusion of Pd into *n*-GaAs.

More detailed studies on solid phase reactions in the Pd/Ge/GaAs have been reported by Grinolds and Robinson[72]. Using AES, X-ray diffraction, I–V and C–V measurements they have shown that the sintering process consists of three stages. In the initial stage, at temperature below 300°C interdiffusion and reaction between Pd and Ge form two polycrystalline phases Pd_2Ge and PdGe. The Pd–Ge reaction continues until all the elemental Ge has reacted with Pd; the presence of unteacted Ge prevents the Pd–GaAs reaction. Sintering at temperatures above 300°C produces the reaction between Pd and GaAs. Above 400°C Ge penetrates into GaAs and ohmic contact is formed. The formation of ohmic contact is attributed to the interaction between Pd and GaAs which alters the relative number of Ga to As vacancies and causes the incorporation of Ge on Ga sites.

Anderson *et al.*[73] investigated sintered ohmic contacts to *n*-GaAs using epitaxial Ge films and Ni, Ta or Mo overlayers. Starting with single crystal Ge layer and a thoroughly cleaned GaAs surface results in a very homogeneous interface and a uniform doping profile. AES sputter profiles from Ni/Ge contacts revealed the enhanced diffusion of Ge into GaAs in the presence of Ni and showed the necessity for the use of a nickel overlayer. The penetration of Ge into GaAs, together with the fact that a *p–n* junction is created when a Ni/Ge contact is made on *p*-GaAs indicated that Ge is the species responsible for obtaining a highly doped n^+ layer at the interface.

Au, Pt, Ti were also tried as sintered contacts to n^+ and p^+-GaAs ($N_{D,A} \sim 10^{18}\,cm^{-3}$)[71]. Contacts to n^+-GaAs were rectifying. Good ohmic behaviour was observed for Pt/p^+-GaAs contacts sintered at 350°C for 2 hr; specific contact resistance of $4.2 \times 10^{-4}\,\Omega cm^2$ was achieved. Au and Ti were only partly effective in forming ohmic contacts to p^+-GaAs. $PtAs_2$, Pt_3Ga and

Table 1. Sintered ohmic contacts to *n*-GaAs

Metallization		Sintering			Semiconductor doping (cm^{-3})	Specific contact resistance ($\Omega\, cm^2$)	Ref.
Contact system	Thickness (Å)	Temperature (°C)	Time (min)	Atmosphere			
Pd/Ge	500/500	500	120	Vacuum	1.2×10^{16}	3×10^{-4}	71
					10^{17}	1.7×10^{-4}	
					1.5×10^{18}	3.5×10^{-5}	
Pd/Ge	1250/410	500	20	Flowing N_2	1.1×10^{16}	3×10^{-1}	72
		550				2.5×10^{-3}	
		600				3.5×10^{-4}	
		500	20		2.0×10^{17}	2×10^{-3}	
		550				3.5×10^{-4}	
Ni/Ge	1000/1000	550	5	Vacuum or flowing gas	1.1×10^{17}	3×10^{-5}	73
Ta/Ge		650				5×10^{-4}	
Mo/Ge		750					

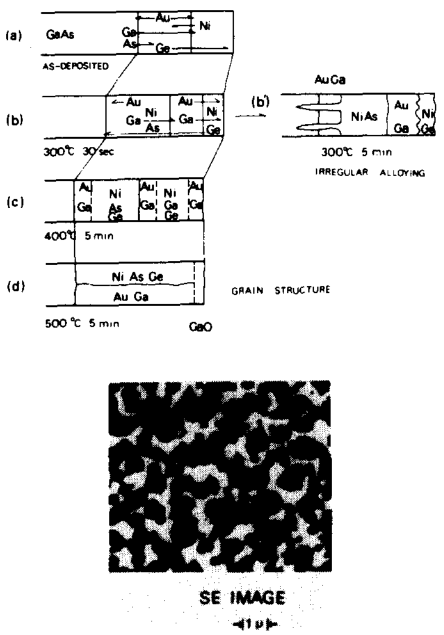

Fig. 3. Model of Ni/Au–Ge/GaAs contact system alloying (from Ref. [63]). The SEM photograph corresponds to the last step (d). The AuGa and NiAsGe grains are respectively bright and dark.

TiAs intermetallic compounds were found in sintered Pt/p^+-GaAs and Ti/p^+-GaAs structures.

3.1.3 *Laser and electron beam annealing.* The first ohmic contacts to III-V semiconductors prepared by laser annealing had the specific contact resistance in the range from 10^{-3} to $10^{-4}\,\Omega\,\mathrm{cm}^2$. Great progress has been accomplished; now the annealing of multicomponent metal structures for ohmic contacts purposes by laser and electron beam is regarded as a really advantageous technique.

A common observation reported by workers investigating the properties of pulse annealed contacts is the superior surface morphology and smaller redistribution of contact constituents. The reduction of heating time diminishes (a) the loss of the volatile components of III-V semiconductors, (b) the intermixing of metals and semiconductors and (c) phase segregation and size of grains.

Moreover, since bulk heating is avoided, the properties of the active structure of the device are not affected during the ohmic contact annealing.

Margalit *et al.*[74] using Q-switched ruby laser reduced the specific contact resistance of Au–Ge/n-GaAs contacts from $r_c \simeq 5\times10^{-4}\,\Omega\,\mathrm{cm}^2$ to $r_c \simeq 7\times10^{-5}\,\Omega\,\mathrm{cm}^2$. AuGe and AuGeNi contacts to n-GaAs with specific contact resistance of $2\times10^{-6}\,\Omega\,\mathrm{cm}^2$ have been reported by Gold *et al.*[75]. Contacts were annealed by a CW Ar laser and pulsed ruby laser. The main disadvantage of these contacts was poor reproducibility attributed partly to GaAs surface preparation. Eckhardt *et al.*[76, 77] investigated AuGeNi, AuGeAg, AuGeTi and AuGeIn contacts to n-GaAs using CW Ar, pulsed CO_2, pulsed Nd:YAG and pulsed ruby laser. The best results with regard to specific contact resistance, adhesion and reproducibility were obtained with the CW Ar laser. A backside-irradiation technique with Q-switched Nd: glass laser ($\lambda = 1.06\,\mu$m) has been used by Oraby *et al.*[78] to produce Au–Ge ohmic contacts to n-GaAs. Ohmic contacts with a specific contact resistance r_c less than $2\times10^{-5}\,\Omega\,\mathrm{cm}^2$ have been obtained, while thermally alloyed contacts yielded $r_c = 1.3\times10^{4}\,\Omega\,\mathrm{cm}^2$.

A Q-switched Nd : YAG laser has been used by Salathé *et al.* [79] to produce stripe geometry ohmic contacts in GaAlAs/GaAs DH lasers. The contact formation has been performed directly on the p-type GaAlAs layer using a Zn(1%)-Au(99%) layer 0.5 μm thick. Stripe widths from 5 to 15 μm were generated by 30 ns pulses with power density from 300 to 600 MW/cm^2 through a cylindric lens system.

Only few experiments has been made on contact annealing with pulsed electron beam. PEBA annealed AuGeNi, AuGePt, AuGeAg contacts to n-GaAs were reported by Eckhardt[76]. The main disadvantage, apart from a higher (than for laser-annealed) resistivity was poor contact adhesion after annealing partly explained by a contact layer thickness not optimized for PEBA.

AuGe/Pt contacts to n-GaAs with a specific contact resistance of $4\times10^{-7}\,\Omega\,\mathrm{cm}^2$ have been achieved by Tandon *et al.*[80]. The reduction of r_c (from $1.3\times10^{-5}\,\Omega\,\mathrm{cm}^2$ for furnace alloyed) and good surface morphology were attributed to little mixing of Ga and As with the metal layers during the short-time alloying process.

The summary of results on pulse annealed contact is presented in Table 2.

3.1.4 *Summary of experimental results.* A summary of published experimental results on ohmic contacts to GaAs and InP produced by means of annealing of multicomponent metal structures is presented in Figs. 4–7. It shows the values of specific contact resistance obtained with different contact systems for various doping level of bulk semiconductor. In every case reference is made to the method of contact annealing. The references give technological details of contact fabrication such as the method of contact deposition, the metallization thickness and the heat treatment procedure.

Theoretical curves $r_c = f(N_{D,A})$ for various values ϕ_B indicate the values of specific contact resistance for perfect metal—semiconductor contact. They allow to compare the efficiency of various contact technologies. For the experimental values of r_c lower than $r_c = f(N_{D,A}, \phi_B)$ one can suggest that the use of metallization with dopant element increased the doping level of the semi-conductor surface after annealing. The results as a whole indicate strongly that after heat treatment the doping level of semiconductor in the contact region increases, i.e. they suggest that the formation of ohmic contact is mainly the results of the doping action of active

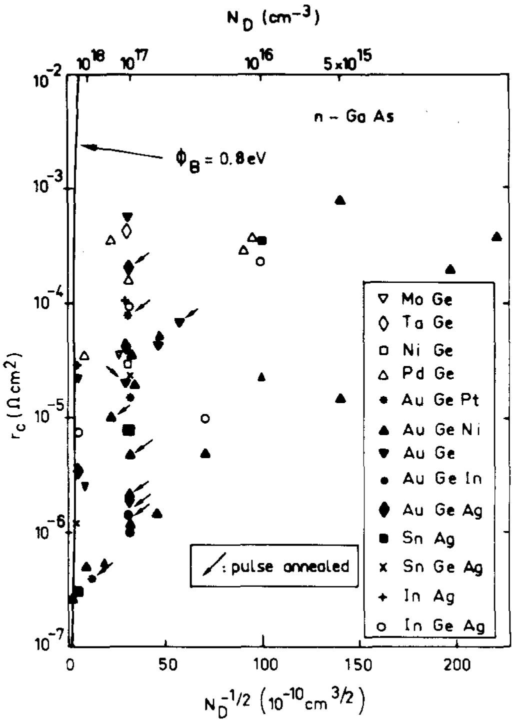

Fig. 4. Experimental results on alloyed ohmic contact to n-GaAs. From Refs. [73] for MoGe ▽, TaGe ◇, NiGe □; [71, 72] for PdGe △; [76, 78] for AuGePt ∗; [41–50, 74–77, 124, 160] for AuGeNi ▲; [46, 73, 75, 78, 165, 166] for AuGe ▼; [76] for AuGeIn ●; [49, 76] for AuGeAg ◆; [49] for SnAg ■, SnGeAg ×, InAg + and [44, 49] for InGeAg ○.

Table 2. Pulse annealed ohmic contacts to *n*-GaAs

Metallization		Annealing conditions				Semicond. doping (cm^{-3})	Specific contact resistance (Ωcm^2)	Ref.
Contact system	Thickness (Å)	Irradiation		Energy density (j/cm^2)	Pulse duration			
AuGe/Ni/Au	1200-1700/400/500-600	CW Argon laser	$\lambda = 0.51 \mu m$	0.64	0.43 cm/s	10^{17}	4.8×10^{-6}	76
AuGe/Pt/Au				0.61	0.43 cm/s		1.5×10^{-5}	
AuGe/Ag/Au				0.66	0.43 cm/s		2.0×10^{-4}	
AuGe/Ti/Au				1.35	0.20 cm/s		1.8×10^{-5}	
AuGe/In				0.56	0.43 cm/s		1.3×10^{-6}	
AuGe	200/100/Ge top layer	"free-running" pulsed ruby laser	$\lambda = 0.6943 \mu m$	~ 10	1 ms	10^{17}	2×10^{-6}	75
Au/Ge/Ni	200/100/20						2×10^{-6}	
Au/Ge/Ni/Au	1500/400/500	pulsed ruby laser	$\lambda = 0.6943 \mu m$	0.8	30 ns	2×10^{17}	10^{-5}	77
AuGe	3000	Q-switched ruby laser	$\lambda = 0.6943 \mu m$	1.02	15 ns	3×10^{16}	$7.04\text{-}5.14 \times 10^{-5}$	74
AuGe	300-1200	Backside irradiation Q-switched Nd : glass laser	$\lambda = 1.06 \mu m$	0.3-0.5	20 ns	$> 10^{17}$	2×10^{-5}	78
AuGe/Ni/Au	1200-1700/400/500-600	pulse electron	E = 10-12 keV	0.28	100 ns	10^{17}	3.5×10^{-5}	76
AuGe/Pt/Au				0.28			8.6×10^{-5}	
AuGe/Ag/Au				0.32			2.3×10^{-5}	
AuGe/Pt	1300/300	pulse electron	E = 20 keV	0.3 - 0.5	10^{-7} s	7×10^{17}	4×10^{-7}	80

species from multicomponent metallic structures. In some cases, however, for example for Au-Zn contacts to heavily doped p-GaAs, r_c is found to be equal or even higher than for pure Au. We think that here, overdoping, by Zn is ineffective due to the high substrate doping and so variations in r_c could be explained by differences in experimental conditions and thus in contacts morphology.

Consequently, the preparation of heavily doped semiconductor surfaces prior to metal deposition appears very attractive as a method of fabrication of non-alloyed ohmic contacts.

3.2 *Formation of heavily doped semiconductor surfaces for ohmic contacts purpose*

3.2.1 *Diffusion.* Diffusion is the most classical way to obtain highly doped surface layers. With regard to III-V compound semiconductors however, it was successfully applied mainly for p-type dopants only.

Concerning ohmic contact formation two specific problems can arise with this method. One is that the temperature required for diffusion may be incompatible with the device fabrication process, and the second is the diffusion depth which may be incompatible with thin layered structures. However, when diffusion is used in the formation of active structures the carrier concentration on the surface is often high enough to form a tunnelling metal—semiconductor junction. Cr-Au or Ti/Au might be then used as ohmic contacts in GaAlAs/GaAs LEDs and lasers[81–87] and GaInAs/InP photodiodes[88,89]; Au was used in planar diffused GaAs varactor diodes[90], Al in GaP and GaAsP LEDs[91,92].

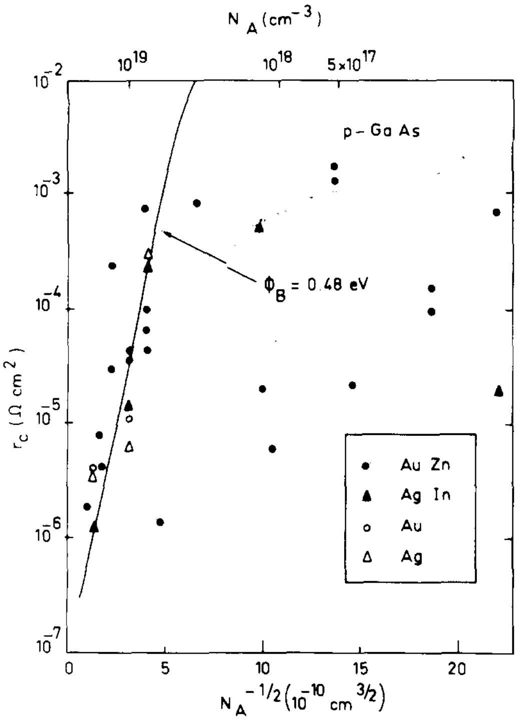

Fig. 5. Experimental results on alloyed ohmic contacts to p-GaAs. From Refs. [38–40, 51, 54] for AuZn ●; [49, 53] for AgIn ▲ and [49] for Au ○ and Ag Δ. ——— is the theoretical curve $r_c = f(N_A)$ for $\phi_B = 0.48$ eV.

With Zn, the most currently used p-type dopant, surface concentrations as high as $10^{19}-10^{20}$ cm^{-3} may be obtained[93–97] in GaAs, GaAsP, GaInAs and except with InP it is relatively easy to obtain ohmic contacts to p-type diffused layers of III-V compound semiconduc-

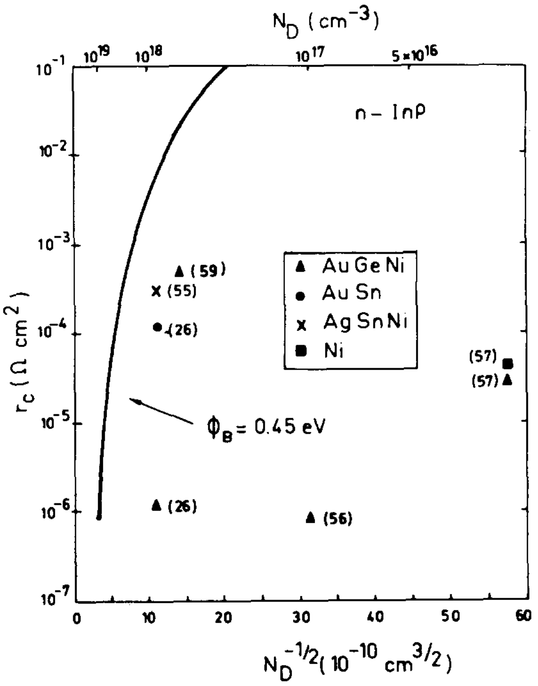

Fig. 6. Experimental results on alloyed ohmic contacts to n-InP. ——— is the theoretical curve $r_c = f(N_D)$ for $\phi_B = 0.45$ eV.

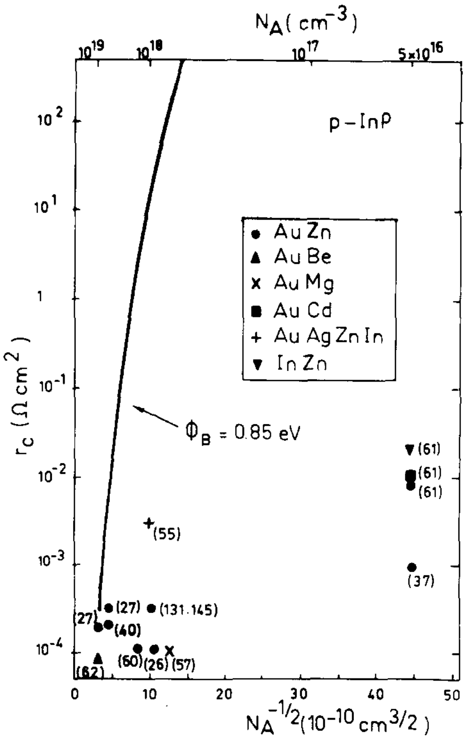

Fig. 7. Experimental results on alloyed ohmic contacts to p-InP. ——— is the theoretical curve $r_c = f(N_A)$ for $\phi_B = 0.85$ eV.

tors. The use of diffusion for ohmic contact purposes has been reported by several workers. Shallow Sn diffusion was performed on Ge doped GaAs LPE layers in GaAlAs/GaAs lasers with Ti/PtAu[98] or Cr/Au[85] as p-type metallization. It was also applied to p-GaAlAs in GaAlAs/GaAs lasers[83, 99] and detectors[100] with Cr/Au or Ti/Pt as ohmic electrodes. The use of Zn diffusion to reduce ohmic contact resistance to p-InP[101, 102] and p-GaInAsP[103–105] has been also reported. In this case, however, the improvement of ohmic contacts characteristics resulting from the Zn diffusion is perhaps not sufficient and Au–Zn alloyed contacts are often applied even to Zn-diffused contact layers[103–104].

Diffusion in III-V compound semiconductors is usually carried out by furnace heat treatment and the problems which arise with the dissociation of III–V semiconductor and the surface loss of elements from group-V are traditionally circumvented by maintaining an overpressure of the group-V elements in a sealed ampulla. Alternatively, diffusion is performed in an open ampulla with a controlled atmosphere that includes the volatile component.

Recently, pulsed diffusion has been proposed as a way of forming highly doped layers. Davies *et al.*[106] used a pulsed electron beam to diffuse Se into GaAs. An As_2Se_3 film deposited on the GaAs surface was used as source. The use of a low melting point source and the creation of an instantaneous overpressure of As by the pulse were believed to help in overcoming the loss of arsenic from the GaAs surface. The diffusion from the As_2Se_3 layer with an electron beam power of $1.0\,\mathrm{J/cm^2}$ resulted in a doping of $\sim 3.10^{19}\,\mathrm{cm}^{-3}$ and a penetration to ~ 2000 Å. The reduction of doping level observed at the very surface was overcome partly by reducing the energy of the diffusion pulse (to $0.7\,\mathrm{J/cm^2}$), partly by removing part of the surface layer.

3.2.2 *Ion implantation.* Another proven approach for introducing dopants is shallow ion implantation with high doses. The major problem with this technique lies in the radiation damage introduced by the implanted ions into the host material. A post implant treatment which anneals out the defects and activates the dopant is required. Since the temperatures needed for this step may be of the order of 900–1000°C, care must be taken to minimize the effects of thermal dissociation of the III–V semiconductors, in particular the loss of the metalloid. During furnace annealing it is customary to prevent molecular dissociation by the use of an encapsulant.

Hot implantation or dual implantation is also useful for the activation of high dose implants[107–109]. Recently laser annealing[110–118] and pulse-electron beam annealing[118–122] have been successfully applied to implanted III–V compounds. Generally, pulse annealings gave better results than furnace annealing, higher dopant concentrations were obtained[118–120]. Short heating time reduced molecular dissociation, fast freeze epitaxial regrowth resulted in a better annealing of the regions of ion-implant damage. There are still certain deficiencies in these techniques such as for example the introduction by the pulse annealing itself of electrically active defects[123]. Nevertheless, implantation followed by pulse annealing must be regarded as very advantageous in comparison with conventional techniques.

The results of work on the formation of ohmic contacts to III–V compounds by ion implantation are presented in Table 3.

Ohata *et al.*[124] performed a selective Si implantation to form n^+ layers in source and drain regions of GaAs MESFETs. Ohmic electrodes were formed by alloying Ni/AuGe films. With an n^+ layer about 0.3 μm thick (peak carrier concentration $n^+ > 10^{18}\,\mathrm{cm}^{-3}$) the specific contact resistance was reduced to $5 \times 10^{-7}\,\Omega\,\mathrm{cm}^2$ while without the n^+ region the resistance was equal to $1 \times 10^{-6}\,\Omega\,\mathrm{cm}^2$. C.P. Lee *et al.*[162] also reported r_c values of same order of magnitude ($6 \times 10^{-7}\,\Omega\,\mathrm{cm}^2$) for AuGeNi contacts on implanted semi-insulating GaAs.

Multiple ion implantation, as reported by Zuleeg *et al.*[125] was used to form n^+ ohmic contact region in GaAs normally—off mode FET. GaAs was implanted with Se^+ ions with three different energies and doses in order to get flat profiles; another Se^+ implant formed the active layer. Ohmic contacts were fabricated with a AuGe eutectic alloy and a Au overlayer.

Dual (Se + Ga) implantation was used by Inada *et al.*[47] to obtain low resistivity AuGeNi contacts to GaAs. Special efforts were made to maintain the GaAs stoichiometry necessary for the high electrical activation of the implanted Se. An additional Ga implant maintained this high activation after the high dose Se implantation, an oxygen free encapsulant was shown[126] to depress the outdiffusion of Ga during annealing. Ohmic contacts were made by vacuum evaporation of a AuGe/Ni structure (1500/400 Å) and alloying (at 420°C in flowing H_2 gas). For a 0.11 μm thick n^+ layer with a maximum carrier concentration $1.8 \times 10^{19}\,\mathrm{cm}^{-3}$ (at a depth ~ 600 Å) a specific contact resistance of $2.9 \times 10^{-7}\,\Omega\,\mathrm{cm}^2$ has been achieved.

Mozzi *et al.*[127] obtained ohmic contacts to n-GaAs with a low resistivity without alloying by means of a Ti/Pt/Au metallization and a n^{++} surface layer created by high dose Se implantation. Post—implant annealing was performed by pulse—electron beam. No protective cap was used either during implantation or during annealing. A surface precipitate, presumably a Ga-rich residue resulting from the outdiffusion of As during anneal was removed in HCl. With a 0.2 μm thick n^{2+} layer a maximum carrier concentration of $1.2 \times 10^{19}\,\mathrm{cm}^{-3}$ was obtained (at a depth ~ 0.12 μm). The metallization was produced by e-beam vapor deposition of 1000 Å Ti, followed by 1000 Å of Pt and 3000 Å of evaporated Au.

A high donor concentration of $n = 4 \times 10^{19}\,\mathrm{cm}^{-3}$ obtained by means of PEBA of Se-implanted GaAs was reported by Pianetta *et al.*[128]. Nonalloyed Al ohmic contacts formed without surface etching had the specific contact resistance r_c of $6 \times 10^{-6}\,\Omega\,\mathrm{cm}^2$.

Non alloyed Ti/Pt ohmic contacts produced by laser annealing of n-GaAs implanted with Te have been reported by Barnes *et al.*[129, 130], RBS and channeling measurements indicated a Te concentration greater than 10 times the equilibrium solubility with 90% of the Te on

Table 3. Ohmic contacts fabricated by means of ion implantation to III-V compound semiconductors

Semiconductor	Implanted ion	Implantation conditions (dose, energy, temperature)	Annealing		Ohmic contact		Ref.
			Method	Conditions	Metal	Specific contact resistance	
n-GaAs	Si	7×10^{13} cm^{-2}, 40 KeV 1×10^{14} cm^{-2}, 100 KeV R T	furnace, N_2	800°C, 20 min CVD SiO_2 encapsulant	AuGeNi	5×10^{-7}	124
n-GaAs	Se Ga	4.4×10^{14} cm^{-2}, 100 KeV 5×10^{14} cm^{-2}, 90 KeV 400°C	furnace, N_2	950°C, 15 min CVD Si_3N_4 encapsulant	AuGeNi	$\leqslant 2.9 \times 10^{-7}$	47
n-GaAs	Se	$\left.\begin{array}{l} 1.3\times10^{14}\ \mathrm{cm}^{-2}, 190\ \mathrm{KeV} \\ 2.6\times10^{14}\ \mathrm{cm}^{-2}, 100\ \mathrm{KeV} \\ 6.5\times10^{14}\ \mathrm{cm}^{-2}, 50\ \mathrm{KeV} \end{array}\right\}$ RT $2\text{-}4\times10^{12}$ cm^{-2}, 200 KeV 300°C	furnace, H_2	750-925°C, 20 min sputtered Si_3N_4 encapsulant	AuGe	-	125
n-GaAs	Se	5×10^{15} cm^{-2}, 120 KeV R T	pulse electron beam	$E = 10 - 15$ KeV $\Delta t = 150$ ns $P = 0.71$ J/cm^2	TiPtAu	$\leqslant 6 \times 10^{-7}$	127
n-GaAs	Te	10^{16} cm^{-2}, 50 KeV, RT	Nd:YAG laser	$\lambda = 1.06$ μm $\Delta t = 125$ ns $E = 20$ MW/cm^2	TiPt	2×10^{-5}	129
n-GaAs	Se	5×10^{15}cm, 50 KeV, 350°C	pulse electron	$E = 12$ KeV $\Delta t = 80$ ns $P = 0.65 - 0.9$ J/cm^2	Al	$< 6 \times 10^{-6}$	128
p-InP	Zn	3×10^{15}cm^{-2}, 30KeV, RT	Nd:YAG laser Nd:YAG laser ruby laser	$\lambda = 1.06$ μm $t = 200$ns $J = 0.5$ J/cm^2 $\lambda = 0.53$μm $\Delta t = 300$ns $\lambda = 0.694$μm $\Delta t = 50$ns	Au	$(0.5 - 2) \times 10^{-4}$ $(0.8 - 2.4) \times 10^{-3}$ $> 10^{-2}$	131,132

substitutional sites and a good recrystallization of the implanted layer. However, the surface topography was rough and subsequent surface treatment (removing of Ga in HCl, and removing of about 50 Å GaAs by *rf* back-sputtering in Ar) was required before the metallization step. Ohmic contacts were made by *rf* sputtering of Ti (1000 Å) followed by 1500 Å of Pt.

Ion implantation followed by a laser annealing to produce non-alloyed Au contacts to *p*-InP were reported by Liau *et al.*[131, 132]. Zn or/and Cd were the implant species, Nd : YAG and Q-switched ruby lasers were used for the post-implant annealing, the Au ohmic contacts were fabricated by vacuum evaporation. The specific contact resistance on layers implanted with Zn^+ was about a factor of 2 lower than on layers implanted with Cd^+. An increase in Cd^+ dose from $3\times10^{15}\,cm^{-2}$ to $7\times10^{15}\,cm^{-2}$ gave only ~30% improvement. Contact resistances about 40% lower were obtained for double Zn^+ and Cd^+ implantation (3×10^{15} Zn/cm^2 and 1×10^{15} Cd/cm^2). It was shown that the specific contact resistance depends critically on the wavelength, duration and power density of the laser pulse. The Zn depth distribution measured by SIMS showed a depletion of Zn in the surface region of InP annealed with ruby laser. The shorter pulse of the ruby laser and the greater initial absorption resulted in a much higher transient surface temperature. This caused a greater loss of phosphorus and of the implanted dopant, owing the evaporation; consequently, the contact resistance was higher.

3.2.3 *Epitaxy.* Double epitaxy relies on epitaxial growth of special semiconductor layer for ohmic contact purposes. The growth of a highly doped layer may be obtained by liquid phase epitaxy (LPE), vapour phase epitaxy (VPE), or molecular beam epitaxy (MBE).

Using Ge as a dopant and suitably modifying the LPE process, Ketchov[133] obtained *p*-GaAs with a carrier concentration of $8\times10^{19}\,cm^{-3}$ and used nonalloyed Cr-Au ohmic contacts in DH lasers.

GaAs contact layers produced by VPE with a *S* doping were used under the source and drain electrodes in power MESFET's by Fukuta *et al.*[134]. A doping concentration of about $3\times10^{18}\,cm^{-3}$ and specific contact resistance less than $1\times10^{-6}\,\Omega\,cm^2$ were achieved. Ohmic contacts were made by AuGe deposition and alloying. The use of n^+ VPE contact layer was also reported for other microwave devices (Gunn diodes, IMPATT's) [135–137].

Mozzi *et al.*[138] obtained non alloyed Ti/Pt/Au ohmic contacts with a low resistivity, ($r_c \sim 10^{-6}\,\Omega\,cm^2$) on VPE n^+-GaAs layers doped with Si. The high doping level was achieved by the reduction of available gallium during epitaxial growth providing *n*-type sites for the amphoteric impurity.

Recently, heavily doped layers of GaAs were successfully grown using MBE[139, 149]. Tsang[140] obtained layers doped with Sn to $n = 8\times10^{18}\,cm^{-3}$ and with Be to $p = 3\times10^{19}\,cm^{-3}$. For ohmic contact purposes an additional transition region from these heavily doped layers to degenerate or almost metallic surfaces was formed by (a) reducing the Ga flux gradually but quickly to zero, (b) decreasing at a much slower rate the As pressure and (c) maintaining the dopant flux constant. With this technique one could obtain non-alloyed contacts of evaporated Au with specific contact resistances between mid-$10^{-5}\,\Omega\,cm^2$ and low-$10^{-6}\,\Omega\,cm^2$ for GaAs doped in the range from 10^{16} to $10^{18}\,cm^{-3}$. Barnes and Cho[139] prepared MBE layers of *n*-GaAs doped with Sn with $n = 6\times10^{19}\,cm^{-3}$. Non alloyed ohmic contacts formed by sputtering of a Ti/Pt (1000 Å/1500 Å) overlayer had a specific contact resistance $1.86\times10^{-6}\,\Omega\,cm^{-2}$. For a doping level of $\sim10^{19}\,cm^{-3}$ the resistivity increased to 10^{-4}–$10^{-3}\,\Omega\,cm^2$.

The most notable successes with double epitaxy as a means of producing ohmic contacts were obtained with C.W. lasers and LEDs. The use of an epitaxial top layer has become common practice to facilitate the formation of low resistance ohmic contacts to the *p*-side of GaAlAs/GaAs and GaInAsP/InP double heterostructures. In this case, the reduction of specific contact resistance is realized by the use of a heterojunction formed by the epitaxial growth of a semiconductor contact layer with suitable bandgap. In GaAlAs/GaAs DH *p*-GaAs is currently formed as contacting cap layer[81, 84, 85, 87, 98, 141, 142]. When the carrier concentration in the gap layer is high enough (for example in devices with active structure formed by Zn diffusion) Cr/Au or Ti/Au are applied as contact metal.

Low resistivity ohmic contacts to *p*-type InP are much more difficult to obtain than for any other *p*-type III–V compound semiconductor. Since the active Zn concentration for LPE InP is limited to $\sim4\times10^{18}\,cm^{-3}$ [143, 144] even the alloyed contacts are often of higher resistance than desired for stripe-geometry lasers. The lowest reported value of AuZn contact is $3-5\times10^{4}\,\Omega cm^2$[37, 145]; a lower reported value of $8\times10^{-5}\,\Omega\,cm^2$ has been shown only with AuBe alloyed films[62, 146]. Consequently, the use of a heteroepitaxial top contact layer to the *p*-side of GaInAsP/InP DH has been demonstrated as necessary to obtain low specific contact resistance.

The results of Nakano *et al.*[60] on AuZn contacts on GaInAsP showed that the decrease of the GaInAsP energy gap is followed by a decrease of contact resistance. Ohmic contacts were prepared by vacuum evaporation of a 1500 Å Au–Zn film (from a 10 wt% AuZn alloy source) and subsequent annealing in H_2 (410–480°C, 20 s). A higher r_c was obtained for InP. For ternary InGaAs with $p = 4.9\times10^{18}\,cm^{-3}$ contacts with $r_c = 1.6\times10^{-5}\,\Omega\,cm^2$ were achieved.

Nagai et Noguchi[147] reported specific contact resistance of $6\times10^{-5}\,\Omega\,cm^2$ for AuZn contacts to the top $Ga_{0.14}In_{0.86}As_{0.32}P_{0.68}$ contact layer ($p = 1\times10^{19}\,cm^{-3}$); ohmic contacts were made by vacuum evaporation and alloying.

Casey *et al.*[148] achieved a specific contact resistance of $3.6-4\times10^{-5}\,\Omega cm^2$ for pulse plated AuZn (16 at % Zn) contact to LPE GaInAsP.

A quaternary $In_{0.79}Ga_{0.21}As_{0.44}P_{0.56}$ layer was used for contact purposes in LEDs[149,150]. A specific contact resistance of $1\times10^{-5}\,\Omega\,cm^2$ was obtained for alloyed (420°C, 5 min) Au/Zn-Au (2.5 wt% Zn) contacts when $p = 5\times10^{18}\,cm^{-3}$[150].

Oe *et al.*[151, 152] used as a cap layer LPE $Ga_{0.17}In_{0.83}As_{0.37}P_{0.63}$ a Cr/Au ohmic contact alloyed at 380°C was used as metallization. Ti/Au contacts have been reported as suitable for *p*-GaInAs[13, 88].

4. INTERFACIAL REACTIONS IN METAL—SEMICONDUCTOR CONTACTS

In the previous paragraph, we have reviewed the fabrication techniques for ohmic contacts to III-V compound semiconductors.

Most works on ohmic contacts to III-V compound semiconductors do not consider chemical reactions at metal—semiconductor interface and treat the ohmic contact formation as a result of pure doping action of an active element introduced into the contact system. The height of the potential barrier of the metal—semiconductor contacts is believed to remain constant and the dominant mechanism of current flow, to be the field emission through a very thin depletion layer of highly doped semiconductor. Such model of an ohmic contact follows partly the fact that most of published works concern the electrical properties only. Since the compositional analyses of these structures are difficult, less is known about the detailed contact structure.

However, the evidence of interfacial reactions and binary compounds formation at the interface was given for most of metal/III-V compound semiconductor systems. They are of fundamental importance both from theoretical as well as technological viewpoints. In this paragraph, we shall first discuss the above mentioned problem of interfacial reactions in metal/III-V compound semiconductor system and then present the problems related to the interface morphology and to the contact reliability.

4.1 *Compound formation*

Up to now, it was admitted that two types of interactions occur in metal/III-V compound semiconductor contacts[69]. The first occured in the case of near noble metals and was characterized by phase transformation and compound formation. Pt/GaAs, Pt/Ti/GaAs, Pd/GaAs, Rh/GaAs and Pt/GaP contacts were the examples. PtGa and $PtAs_2$ arranged in the form of fairly well-defined layers were found as reaction products in Pt/GaAs contacts; TiAs, $PtAs_2$, Pt_3Ga in Pt/Ti/GaAs for instance. The second group included the structures in which interdiffusion of contact constituents was regarded the dominant interaction. Gold contacts (and of other noble metals) were indicated as belonging to the latter group. The interpretations of the interaction of Au with III-V compound semiconductors implied the transfer of the group III component from the semiconductor into and through the gold film, and the indiffusion of Au into semiconductor. The metalloid, liberated at the interface, was believed to be released in an elemental form through the metal. But recently, binary compounds have been identified in noble metal contacts also. After annealing treatment above 400°C Au_7Ga_2 (and/or β-AuGa with Ga = 21 at %) was found in Au/GaAs and Au/GaAlAs contacts[68, 153]. In the same way, after a 500°C anneal the interfacial layer of Au/GaP contacts is not a diffusion layer but a hexagonal β-AuGa phase[154]. In the case of Au/InP contact, our recent metallurgical investigations gave evidence that gold formed compounds with both In and P since 320°C[155, 156]. The reaction products depended on annealing temperature and time. Below 400°C, patches of Au_2P_3 were observed in a Au_3In layer. At higher temperatures, Au_2P_3 traces and Au_9In_4 were found. An equivalent behaviour was observed for Ag/InP contacts where both AgP_2 and $AgIn_2$ phases were identified after heat treatment[157–159].

A compound formation was also detected in little more complex structures. The discussed earlier work by Ogawa[63] gave evidence of the formation of AuGa and NiAs phases in AuGaNi/GaAs contacts. Phase transformations in AuGeNi, AuGeIn, AgGeIn alloyed contacts to GaAs were also reported by Christou[44]. Recently, hexagonal α-AuGa (Ga = 13 at %) and AuGeAs compound (firstly reported by Loveluck[169]) were observed in AuGe/GaAs structure after a 2 min anneal at 400°C but only AuGeAs compound formation and Au and Ge grains growth resulted from the anneal of a AuGe/GaAs contact for 24 hr at 320°[163].

The results of metallurgical investigations presented above suggest a common model of interactions of all metal/III-V compound semiconductor systems used in ohmic contact technology. Contact constituents such as Au, Ag, Pt, Ni, In, Mo, Ta, Ti, Pt, Pd react with semiconductor substrate and form binary compounds at the interface. Although the main action of active elements such as Ge, Si, Zn, Be etc... consists in doping the surface layer of semiconductor, they also form compounds in the interfacial layer (as for example Pd_2Ge, PdGe, $PtGe_2$, GeNi, AuGeAs). In this context, there is no difference in final structure of alloyed and sintered ohmic contacts.

4.2 *Interface morphology*

The main conclusion of metallurgical studies is that a macroscopic model of contact is insufficient. Ohmic contacts cannot be treated as inert junctions between metal and highly doped semiconductor but as contacts between semiconductor and binary compounds formed as a result of interfacial reactions between semiconductor and metallization constituents. The first consequence of the compound formation is a change of interface chemistry, but the most pronounced disadvantages are the microcrystallization effects which often lead to a rough and latterally nonuniform interface. Particle precipitation and solid phase formation mean that the contact properties vary over the whole contact area. Different phases very likely give rise to a nonuniform doping of the semiconductor surface layer and consequently to a nonuniformity of the current density across the contact. This phenomenon can affect in turn the reliability of the contact. As a high and uniform current density is often needed (for instance in GaAs microwaves devices) and a structural uniformity is required (for submicrometer integrated circuits processing) smooth and homogeneous interfaces have to be obtained. The questions arise whether and how the nonhomogeneities of contact structure can be eliminated in alloyed and sintered contacts, i.e. whether new phases formed during contact annealing can grow as layered structures. The answer cannot be univocal since numerous studies have been dealing with the effects of some process parameters as the surface preparation prior metal deposition, the metal layer thickness, the annealing temperature and time, the use of a capping layer.

Strong influence of the semiconductor surface cleaning on contact reaction has been observed in Au/InP system[156]. Different procedures of semiconductor surface treatment influenced the beginning of the reaction due to residual oxides at metal/semiconductor interface restraining the interaction[164]. If the nucleation centres correspond with the sites where oxide layer cracks first, a more effective surface cleaning may increase the number of nucleation centers; then the corresponding reduction of the size of precipitates may lead to better layered structures. However, the precipitate formation in a laterally inhomogeneous structure may also be an intrinsic phenomena which can not be avoided.

The dependence of crystalline structure and/or of the extent of particular phases on temperature and duration of contact annealing was confirmed by a number of works. Higher temperature and longer time caused increasing size of the alloyed region (Au_7Ga_2 phase) in Au/GaAs and Au/GaAlAs contacts[153, 68]. The extent of solid phase epitaxy (Ge–In, Ga–Ni) was a function of annealing temperature in AuGeNi, AuGeIn and AgGeIn contacts to GaAs[44], but rapid heating and cooling procedure was necessary to reduce the irregular penetration of NiAs into GaAs in AuGeNi/GaAs contacts[63]. In this way, due to the short heating time, the use of pulse annealings gives a real chance of improvement of contact homogeneity because considerable diminution of phase segregation were achieved[74, 80]. But recently, contact with morphology superior to conventionally alloyed contacts, have also been made to *n*-type GaAs by sintering AuGe films on GaAs in the relatively low 300°C temperature range[163, 165, 166].

A capping layer was also used with success. So, SiO_2[160] and Si_3N_4[163] films which are chemically inert during alloying in the 450°C temperature range, but exerts a stress tending to hold the film on the surface, were used to decrease the roughness of the alloyed film in AuGe/GaAs contacts.

At last, very smooth and continuous interface was obtained in sintered Ni/Ge/GaAs contacts, by using Ge in form of epitaxial layer[73]. That results both from extremely thoroughly cleaning of GaAs substrate and from very close lattice match between Ge and GaAs.

In conclusion, on the interface morphologly of alloyed and sintered contacts, we can say that the effects of phase segregation can be limited but geometrical effects will probably not be reduced below presently attained status without more refined techniques.

4.3 *Electrical consequences*

The compound formation induces a change of the barrier height (due to the new interface chemistry) and of the morphology, structure and composition of the underlying semiconductor: these facts must be regarded in the analysis of transport properties. Formation of ohmic contacts to *p*-GaAs with pure Au[49] and to p^+-GaAs with Pt[71] can be attributed, at least partly, to the reduction of the barrier height. However, the transformation of our Au/*n*-InP Schottky barrier ($\phi_B = 0.46\,\mathrm{eV}$) into ohmic contacts after a 360°C anneal ($r_c = 2 \times 10^{-3}\,\Omega\,\mathrm{cm}^2$ for $N_D = 4 \times 10^{15}\,\mathrm{cm}^{-3}$) must be attributed both to the decrease of barrier height and to the interface irregularities which enhance the thermionic field emission and are the source of excess of current. In the case of Au/*p*-InP these effects degrade the Schottky barrier but are not sufficient to form an ohmic contact. When dopant atoms are added to the metal film, they diffuse into the substrate and overdope the semiconductor surface layer. However, some of them can form compound with both the metal and the semiconductor atoms. In the case of alloyed Au–Ge based contact on GaAs, microscopic grains of Ge-rich materials are seen to be formed[44, 63, 163]. In a recent paper, N. Braslau[161] claims that the current flows through these Ge-rich islands whose resistance is negligible compared to spreading resistance in series with them. So, the contact resistance seems to be limited by geometrical effects which is in accordance with the decrease of the resistance resulting from an improvement of the surface coverage under a SiO_2 capping [160]. In fact, there is still no satisfactory explanations for the forming and working processes of ohmic contacts[161, 167, 168, 170]: if alloyed and sintered contacts are simple and usable, they are still far from ideal.

4.4 *Contacts reliability*

To avoid aging effects of contacts, the reaction between metal and semiconductor atoms, has been found to reach a stable point. If, for instance, an amount of unreacted Au remains on top of the contact, further development of contact reactions can take place during operation. Since a metal overlayer, readily of Au, is often used for bonding and interconnection purpose, a refractory barrier between ohmic contact and Au overlayer is needed to prevent further reactions.

The same kind of problems are encountered in nonalloyed ohmic contacts produced by metal deposition on highly doped semiconductors (previously doped via diffusion, ion implantation or obtained by epitaxy). The success of this type of ohmic contact technology depends greatly on finding suitable refractory metal systems which yield contacts of high temperature stability.

5. CONCLUDING REMARKS

The present state of technology of ohmic contacts to III–V compound semiconductors has been described.

The presented review gives a whole range of procedures of ohmic contact fabrication. However, the variety of technological approaches reflects rather the difficulties in obtaining satisfactory contacts than the great choice of methods being at the disposal.

From the above given data one can chose a method which permits, in principle, the realization of contacts with lowest specific contact resistance. However, the precise comparison of the results is hindered by the differences in experimental conditions (such as, for example, semiconductor surface preparation) and in the measurements techniques used in various works. However, it should be remembered, that r_c is not the only parameter deciding about the contact usefulness. In practice, some other factors such as device processing and operation, the costs of equipment etc... influence the choice of the method. So, instead of suggestions for "the best method", we found more useful to discuss the problems of the ohmic contact technology, to examine the phenomena responsible for ohmic contact properties and to show the possibilities offered by recently developed methods.

For controlling the properties of ohmic contacts it is necessary to understand the physical phenomena related to the contact formation, performance and reliability. To our feeling, the interfacial reactions, the phase transformations and the contact performances are largely correlated. Whether they are useful in ohmic contact formation (in alloyed and sintered contacts) or they are to be avoided (in nonalloyed contacts), they decide about the success of the contact technology.

The actual tendency in ohmic contact technology consist mostly in the use of highly doped semiconductor surfaces. Up to now, ion implantation is most currently used for this purpose. MBE must be treated as very prospective for obtaining highly doped contact layers and/or heterostructures with suitable bandgap. Very attractive in ohmic contact technology are the techniques of laser and electron beam annealing, both for heat treatment of multicomponent metallic structures as well as for preparation of highly doped semiconductors. Until ageing tests are performed no conclusive remarks about superiority of these methods can be stated however.

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