# W(Zn) selectively deposited and locally diffused ohmic contacts to p-InGaAs/InP formed by rapid thermal low pressure metalorganic chemical vapor deposition

A. Katz, A. El-Roy, A. Feingold, M. Geva, N. Moriya, S. J. Pearton, E. Lane, T. Keel, and C. R. Abernathy

*AT&T Bell Laboratories, Murray Hill, New Jersey 07974*

Self-aligned, locally diffused W(Zn) contacts to InGaAs/InP structures were fabricated by means of rapid thermal low pressure metalorganic chemical vapor deposition (RT-LPMOCVD), using a reactive gas mixture that contained diethylzinc (DEZn), $WF_6$, $H_2$, and Ar. W(Zn) layers of about 30 nm thick were deposited at 500 °C for 20 s and at a total pressure of about 2 Torr, onto InGaAs and InP. Spontaneous formation of highly doped underlying InGaAs and InP layers about 150 nm thick with Zn concentration levels higher than $1 \times 10^{18}$ cm$^{-3}$ took place through the deposition of the W(Zn) layers. Post-deposition, *in situ* annealing at temperatures of 500 °C or lower enhanced the indiffusion of Zn into the underlying semiconductor and reduced the specific resistance of the W(Zn)/InGaAs contact to a minimum value of $5 \times 10^{-6}$ $\Omega$ cm$^{-2}$.

Controlled diffusion of dopants such as Zn into InP and related materials is essential for the formation of well-defined *p-n* junctions in photonic and electronic devices,[1-3] as well as to enhance the creation of highly doped $p^+$ regions to support a high performance ohmic contact.[4-6] Typically, the highly doped regions are fabricated by the incorporation of the dopant through an epitaxial growth of a cap layer. Occasionally, however, this approach does not provide the best solution, due to the need to selectively form a highly doped region only under the contact metal pad itself, such as in the case of heterojunction bipolar transistor (HBTs),[6,7] or when necessary, to eliminate parasitic capacitance in optoelectronic devices. The selective diffusion of dopants such as Zn may be achieved by various techniques; such as applying an open tube diffusion, using Zn doped $SiO_2$, spin-on zinc silica films, closed tube diffusion in As atmosphere,[8,9] and the most conventional approach of diffusing the dopants from a previously deposited metal-alloy layer into the semiconductor by means of furnace or rapid thermal alloying cycles.[10,11]

In this letter, we present results on a Zn indiffusion from a selective rapid thermal, low pressure, metalorganic chemical vapor deposited (RT-LPMOCVD) layer of W(Zn) onto InP and InGaAs substrates. The selective and blanket depositions of conductors such as $TiN_x$ and W[12-13] by means of RT-LPMOCVD were found to be controllable and reproducible processes. The W was deposited from a tungsten hexafluoride ($WF_6$) gas reduced by hydrogen. Adding diethylzinc (DEZn) into the reactive gas mixture, provides the needed Zn to allow for the deposition of a W(Zn) layer, in a blanket or selective manner, for example, onto InGaAs/InP windows that had been previously etched in a $SiO_2$ spacer layer. These metal stripes may then be annealed to diffuse the Zn into the semiconductor in order to form a very highly doped region under the W-based metal, and to allow the realization of ohmic contacts.

W(Zn) films were deposited onto (100)InP substrates and onto InGaAs layers grown previously on InP, by RT-LPMOCVD technique using an A. G. Associates Heta-pulse CVD-800$^{TM}$ system. This is a low pressure, load-locked, horizontal and laminar flow reactor, heated by two sets of high power halogen-tungsten lamps, and is capable of processing a single wafer under inert, hazardous, or corrosive ambients. The quartz chamber is 10 in. long with an elliptic shape cross section, 4 in. wide and 1 in. high.[14]

DEZn and $WF_6$ reduced by $H_2$ and diluted by Ar were used as the reactive gas mixture to deposit the W(Zn) films. The deposition conditions were as follows. The reactive gases were flown at room temperature into the cold chamber, to establish the desired mixture at a total pressure in the range of 2–2.5 Torr, which was found to yield the optimum selective deposition conditions, then the halogen-tungsten lamps were pulsed at maximum power of up to 20 kW to ramp up the wafer temperature at a rate of about 250 °C/s. Typically the pulse temperature was kept in the range of 450–500 °C for durations of 20–80 s. During the heat pulse the reaction was executed by flowing the Ar, $H_2$, $WF_6$, and DEZn reactive gases at rates of 200–250, 2000–2500, 30–40, and 20–120 standard cubic centimeters per minute (sccm), respectively. The wafers were loaded immediately after being deoxidized in 10:1 $HO_2$:HF solution and degreased by means of warm chloroform, acetone, and methanol, into the CVD-800 load-lock chamber.

Auger electron spectroscopy (AES), Rutherford back-scattering (RBS), and scanning electron microscopy (SEM) techniques were used to characterize the W(Zn) film properties. The diffusion profiles were obtained by secondary ion mass spectrometry (SIMS), using a Cameca IMS-4f system. A primary sputtering beam of Cs$^+$ was used to profile the samples in the SIMS measurements with an impact energy of 5.5 keV and positive secondary-ion detection. The background level for Zn was lower than $1 \times 10^{16}$ cm$^{-3}$. A Zn-implanted sample in the InP wafer was used for quantifying the Zn concentration level. The depth scale was defined by measuring the depth of the
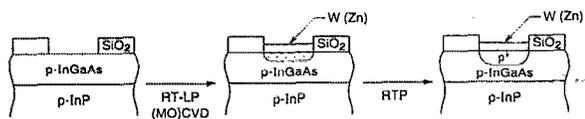
FIG. 1. Schematic representation of the W(Zn)/InGaAs self-aligned locally diffused contact formation by means of RT-LPMOCVD.



FIG. 3. SIMS profiles exhibiting W and Zn concentrations in the RT-LPMOCVD W(Zn)/InP samples.

sputtered craters subsequent to the SIMS analysis. Room-temperature Hall measurements were used to obtain the sample sheet resistance. Electrical properties of the contacts were obtained from transmission line method (TLM) measurements.

Figure 1 provides a schematic description of the structure geometry. This is a typical optoelectronic device cap multilayer structure, in which a p-type highly doped ( > 1 $\times 10^{18}$ cm$^{-3}$) narrow band-gap epitaxial layer, such as InGaAs (0.2–0.4 $\mu$m thick) layer is grown on top of the structure to stimulate the formation of low resistance ohmic contacts. In this study the p-type regions under the metal contact were formed by diffusion of Zn from the W(Zn) films, that were also used as the ohmic contact metallization scheme. Since the W(Zn) metal is selectively RT-LPMOCVD onto the InGaAs/InP over the SiO$_2$ spacers surrounding the contact stripe, this technique provides a method to form a self-aligned Zn diffusion to enhance good ohmic contract formation only over the active layer of the devices.

The selectivity of the RT-LPMOCVD W(Zn) films, is demonstrated with a typical TLM pattern shown in Fig. 2. W(Zn) films (40–60 nm thick) were deposited through a 20–30 s 500 °C cycle, with a deposition rate of 2–3 nm/s, mainly dictated by the deposition temperature. An excellent selectivity was observed while keeping the overall process pressure below 3 Torr and the H$_2$:W flow rate ratio above 70:1.

After achieving the selective RT-LPMOCVD of W(Zn), it was essential to gain control of the Zn indiffusion rates in order to allow for the fabrication of the self-aligned locally diffused contacts. It is well known that Zn can be rapidly diffused into InP at temperatures higher
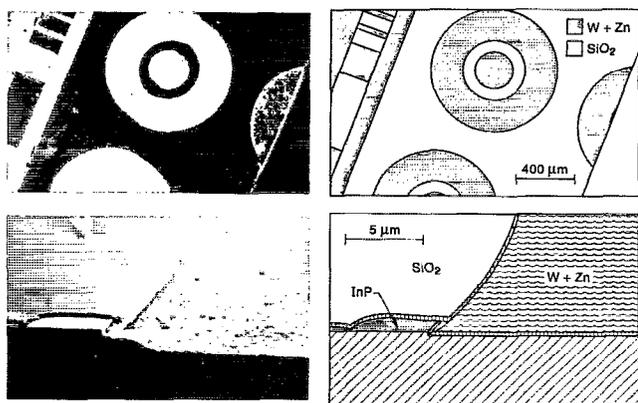


FIG. 2. Scanning electron microscopy micrographs of the RT-LPMOCVD selective deposited W(Zn) metallization onto InGaAs features etched in a SiO$_2$ spacer cap layer.
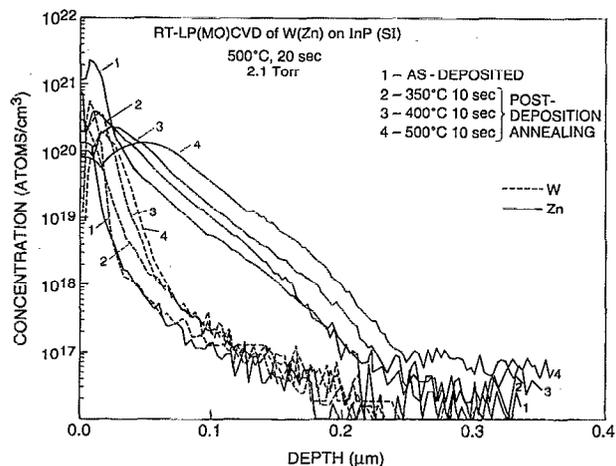
than 500 °C for durations longer than 5 min,[6] realized in diffusion furnaces, sealed-ampoule technique, or through diffusion in MOCVD reactors. These conditions may degrade the InP-based photonic devices and thus are too extreme to be applied in order to drive Zn diffusion out of a metal contact. Therefore the W(Zn) deposition and the diffusion temperatures were reduced to temperatures of 500 °C or lower, and the durations of the heat treatments were reduced to less than 30 s.

SIMS analysis of the as-deposited metal ohmic contact region, as well as similar samples that were in situ thermally annealed after the depositions, are shown in Fig. 3. These profiles demonstrate Zn diffusion into the InP under the W(Zn) metallization already as-deposited at 500 °C for 20 s. An extremely high Zn concentration ( > 10$^{21}$ cm$^{-3}$) is observed at the W(Zn) (30 nm thick) deposited layer, as a result of the gas mixture containing 80 sccm of DEZn and 50 sccm of WF$_6$. One can observe diffusion depths at the Zn level of $1 \times 10^{18}$ cm$^{-3}$ of about 150, 160, 170, and 190 nm, for the as-deposited sample and for the samples that were post-deposition annealed at 350, 400, and 500 °C for 10 s, respectively.

The Zn diffusion depth at the as-deposited sample is about 5 times larger than the W(Zn) metallic layer thickness and exhibits a concentration gradient of about four orders of magnitude over the diffusion depth of about 300 nm. The post-deposition annealing temperature seems to have some effect on the Zn diffusion depth, which was found, however, to be negligible compared to the initial diffusion depth through the deposition.

The Zn diffusion in these samples is associated with interfacial reactions between the W and the InP substrate under it. The shape of the W profiles suggest that an interfacial reaction was promoted by the post-deposition annealing, with a maximum width of about 25 nm as a result of the thermal treatment at 500 °C for 30 s. All the W diffusion profile tailings, however, look similar, which suggest that no W indiffusions took place in these samples.

Figure 4 shows the voltage-current characteristics of the RT-LPMOCVD W(Zn)/InGaAs (Zn doped $1 \times 10^{18}$
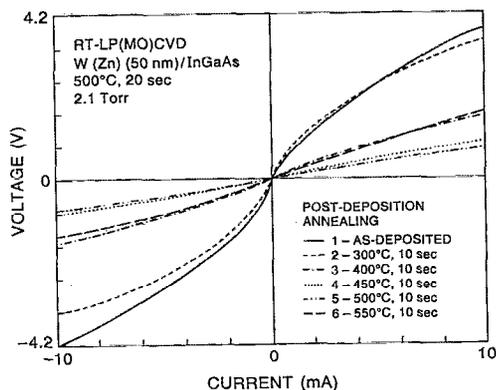
FIG. 4. Voltage-current characteristic of RT-LPMOCVD W(Zn)/ InGaAs contacts, as-deposited and after *in situ* post-deposition annealing at various temperatures for 10 s.

$cm^{-3}$) contacts. The as-deposited contact has a rectifying nature with a measured Schottky barrier height of 0.31 eV. Upon post-deposition annealing at temperatures above 300 °C the contact was converted to an ohmic contact with a minimum specific resistance of $5 \times 10^{-6}$ $\Omega$ cm², when heated at 500 °C for 10 s. The contact resistance reduction as a result of the post-deposition annealing may be attributed to both the metal-semiconductor interfacial reactions and to the Zn indiffusion enhancement. Since a control set of samples, in which pure W was deposited and annealed in the same conditions did not exhibit a similar resistance reduction, it is believed that the ohmic contact performance is dictated by the Zn enhanced indiffusion. The as-deposited W(Zn) layer was found to form a Zn-doped ( $> 1 \times 10^{18}$ $cm^{-3}$) underlayer of about 0.16 $\mu$m thick. The same depth was highly doped ( $> 8 \times 10^{18}$ $cm^{-3}$) as a result of the Zn indiffusion through the 500 °C 10 s post-deposition annealing step. This change in the Zn doping level may be sufficient to yield the significant enhancement of the contact ohmic behavior, as is reflected at Fig. 4. However, some other mechanisms, such as altering the ratio of the substitutional to interstitial Zn in the reactive region through the annealing, may contribute, as well, to this dramatic change.

In summary we have demonstrated the fabrication of self-aligned locally diffused W(Zn) contacts to InGaAs/ InP structures, by means of the RT-LPMOCVD technique. The W(Zn) layers (30 nm thickness) were deposited at 500 °C for 20 s by applying a gas mixture that comprised 80 sccm of Zn and 50 sccm of WF$_6$, and led to a spontaneous formation of an underlying 150 nm Zn highly doped (Zn $> 1 \times 10^{18}$ $cm^{-3}$) InGaAs layer. Post-deposition *in situ* annealing enhanced the Zn indiffusion and led to the formation of a good W/InGaAs ohmic contact with a minimum specific resistance of $5 \times 10^{-6}$ $\Omega$ cm².

[1] J. Wisser, M. Glade, H. J. Schmidt, and K. Heime, J. Appl. Phys. 71, 3234 (1992).
[2] M. Wada, M. Seko, K. Sakakibara, and Y. Sekiguchi, Jpn. J. Appl. Phys. 29, L401 (1990).
[3] C. R. Zeisse, R. Nguyen, L. J. Messick, P. Saunier, and K. L. Moazed, IEEE Electron Device Lett. 10, 358 (1989).
[4] B. L. Sharma, *Semiconductors and Semimetals* (Academic, New York, 1991), Vol. 15.
[5] T. S. Kalkur, Y. C. Lu, and C. A. Araujo, Solid-State Electron. 32, 281 (1989).
[6] Z. F. Paska, D. Haga, and B. Willen, Appl. Phys. Lett. 60, 1594 (1992).
[7] M. Wada, M. Seko, K. Sakakibara, and Y. Sekiguchi, Jpn. J. Appl. Phys. 28, L1700 (1989).
[8] S. K. Ghandi and R. J. Field, Appl. Phys. Lett. 38, 267 (1981).
[9] N. Arnold, R. Schmitt, and K. Heime, J. Phys. D. Appl. Phys. 17, 443 (1981).
[10] S. L. Lester, C. W. Farley, T. S. Kim, B. G. Streetman, and J. M. Antony, Appl. Phys. Lett. 48, 1063 (1986).
[11] S. K. Ghandi, R. T. Hwang, and J. M. Borrego, Appl. Phys. Lett. 48, 415 (1986).
[12] A. Katz, A. Feingold, S. Nakahara, S. J. Pearton, E. Lane, M. Geva, F. A. Stevie, and K. Jones, J. Appl. Phys. 71, 993 (1992).
[13] A. Katz, A. Feingold, S. J. Pearton, S. Nakahara, M. Geva, E. Lane, M. Ellington, and U. K. Chakrabarti, J. Appl. Phys. 70, 3666 (1991).
[14] A. Katz, A. Feingold, S. J. Pearton, and U. K. Chakrabarti, Appl. Phys. Lett. 59, 579 (1991).