Zn Diffusion for High Sensitivity InGaAsN Photodetectors

Jasmine Banks
Electrical Engineering, Virginia Commonwealth University

NNIN REU Site: Lurie Nanofabrication Facility, University of Michigan, Ann Arbor, MI
NNIN REU Principal Investigator(s): Rachel S. Goldman, Materials Science and Engineering, University of Michigan
NNIN REU Mentor(s): Yu Jin, Physics, Materials Science and Engineering, University of Michigan
Contact: banksjl@vcu.edu, rsgold@umich.edu, jinyu@umich.edu

Abstract:

The sensitivity of solid-state photodetectors is often limited by surface leakage current along the etched/cleaved side wall under reverse bias voltage, as shown in Figure 1 (a). A significant reduction in leakage current was recently reported for indium gallium arsenide nitride (InGaAsN), using epitaxial growth of an n-i-n structure, followed by spatially selective surface dopant type conversion during metal-organic chemical vapor deposition re-growth using dimethylzinc and diethylzinc [1-3]. The etched/cleaved surface is thus surrounded by the n-type layer and no longer under bias, as shown in Figure 1 (b). In this summer project, we proposed a novel *ex situ* zinc (Zn) diffusion approach to surface dopant type conversion of n-i-n diodes, using a commercially-available Zn-containing spin-on-glass (SOG). We investigated the influence of annealing time on the diffusion of Zn into gallium arsenide (GaAs). Specifically, we used Hall measurements to investigate the active Zn concentration profiles as a function of annealing time and etch depth. This Zn-SOG surface dopant type conversion approach will be used for the fabrication of low leakage InGaAsN based photodetectors, intended for operation in the 1.3 μm to 1.55 μm wavelength range [4,5].

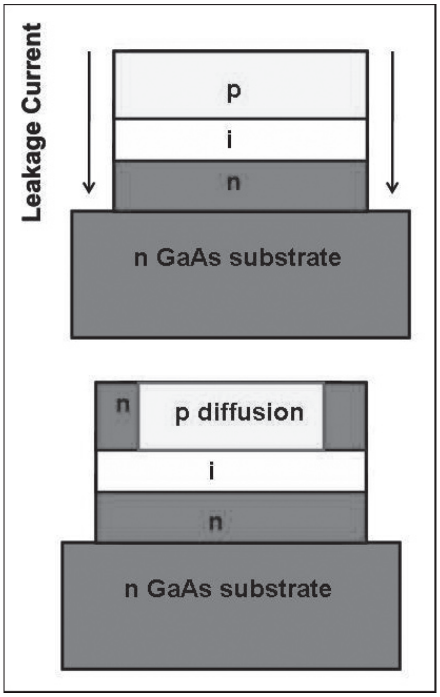

Figure 1: (a) p-i-n photodetector with sidewall leakage current, (b) selectively diffused n-i-n photodetector.

Procedure:

For GaAs:Zn-SOG diffusion studies, the GaAs wafer surface was first conditioned by heating at 350°C to 400°C for a few minutes in air. Zincsilicafilm 306 was then coated on the wafer surface by spin coating at 3000 rpm for 1 minute. After spinning, the wafer was cured by heating in air for 10-15 minutes at 100°C to 120°C [6]. Annealing was then carried out in a quartz furnace with N_2 overflow, with a GaAs proximity cap to prevent As out-diffusion. Following annealing, the Zincsilicafilm was removed by etching in 10% HF, and the surface was examined in an optical microscope. To identify the optimal annealing conditions for photodetector fabrication, the GaAs:Zn-SOG samples were annealed at 850°C for various durations: 15, 20, 23, 30, and 40 minutes.

To characterize the active Zn concentration depth profile, each ~ 1 × 1 cm^2 GaAs:Zn-SOG sample was cleaved into fourths, and one corner of each piece was then coated with photoresist as an etch stop. Following baking for 10 minutes at 130°C, wet etching in H_3PO_4:H_2O_2:H_2O (1:1:25) was carried out for 0, 38, 75, 113 s, resulting in depths of 0, 135 ± 1, 182 ±14, 325 ± 18 nm, as determined by Dektak profilometry. The etched pieces were then cut into ~ 4 × 4 mm^2 pieces, and Hall and resistivity measurements were carried out at room temperature.

Results and Analysis:

We assume that the active Zn concentration profile follows the so-called "finite source" Gaussian diffusion profile, as shown in Figure 2 (a), where x is the depth from the unetched surface, p_0 is the carrier concentration at the unetched

(a)

$$p(x) = p_0 \exp(-\frac{x^2}{2\sigma^2})$$

(b)

$$p_s(x_e) = \int_{x_e}^{\infty} p_0 \exp(-\frac{x'^2}{2\sigma^2})dx' = p_0\sqrt{\frac{\pi}{2}}\sigma(1-erf(\frac{x_e}{\sqrt{2}\sigma}))$$

Figure 2: (a) "finite source" Gaussian profile assumed for Zn diffusion, (b) integration of the profile in (a) to fit the measured residual sheet carrier density as a function of etch depth.

Annealing Time (min)	Carrier Concentration at unetched surface p_0 (10^{20}cm^{-3})	Characteristic Diffusion Length σ (nm)
15	1.30	250
20	1.20	290
23	1.17	320
30	1.09	370
40	1.00	450

Figure 3: Summarizing Carrier concentrations at the unetched surface, p_0, and characteristic diffusion lengths, σ, for samples with various annealing times.

surface, $p(x)$ is the carrier concentration at depth x, and σ is the characteristic diffusion length. The experimentally obtained data cannot be directly fit to the Gaussian profile since the measured sheet carrier density is the total residual carrier density in the film. Therefore, the Gaussian profile was integrated to fit the measured residual sheet carrier density, $p_s(x_s)$, as a function of etch depth, x_s, as shown in Figure 2 (b). For each annealing time, p_0 and σ were then obtained by fitting the measured data to the integrated Gaussian expression, as summarized in Figure 3. As shown in this table, annealing at 850°C for 15 min yields p (200 nm) ~ 9×10^{19} cm^{-3}, which is more than double the n-type dopant concentration in the top of the GaAs photodetector structure (5×10^{18} cm^{-3}), and therefore is sufficient to convert the top layer to p+. Figure 4 shows the best fit Gaussian curve for all of the annealing times, which indicates that as the annealing duration is increased, σ increases and p_0 decreases.

Since a localized active Zn profile is needed to limit the thickness of the i-layer which is converted to p-type, 850°C for 15 min is identified as the optimal annealing condition for the purpose of photodetector fabrication via surface dopant type conversion of n-i-n diodes.

Conclusions:

We proposed a novel *ex situ* Zn diffusion approach to surface dopant type conversion of n-i-n diodes, using a commercially available Zn-SOG. We characterized the Zn diffusion profile for GaAs:Zn-SOG samples and concluded that the 15 minute annealing time produces the optimum profile of electrically active Zn. In the future, this approach will be used to reduce leakage currents in InGaAsN-based photodetectors.

Acknowledgements:

I would to thank God, my family, and friends, Dr. Rachel Goldman, my principal investigator, Yu Jin, my mentor, the Goldman group, the National Nanotechnology Infrastructure Network Research Experience for Undergraduates (NNIN REU) Program, the National Science Foundation, Melanie-Claire Mallison, Trasa Burkhardt, Sandrine Martin, Brandon Lucas, and the LNF staff for all of their help.

References:

[1] Vanhollebeke K; "MOVPE based Zn diffusion into InP and InAsP/InP heterostructures"; Journal of Crystal Growth, 233, 132-140(2001).

[2] Otsuka N., Kito M., Ishino M., Matsui Y., Toujou F.; "Control of double diffusion front unintentionally penetrated from a Zn doped InP layer during metalorganic vapor phase epitaxy"; Journal of Applied Physics, 84, 4239-4247(1998).

[3] Hampel C., Blaauw C., Calder I.D., Glew R., Macquistan D., Bryskiewicz T., Guillon S.; "Metalorganic vapor phase diffusion using dimethylzinc. Part 1 : Analysis of the reproducibility of the resulting diffusion profile as measured by secondary ion mass spectrometry"; Journal of vacuum science and technology, 22, 912-915(2004).

[4] Touam, T., Wu, C., Gigase, Y., Belanger, M., Currie, J. F., Najafi, S. I..; "Fabrication, characterization, and analysis of zinc-diffused GaAs waveguides"; IEEE Journal of Quantum Electronics, 25, 850-853(1989).

[5] Rai S.; "Zinc Diffusion in GaAsSb from spin-on glass dopant sources"; Thesis (M.S.), University of Notre Dame (2004).

[6] http://www.emulsitone.com/znsif_306.html; "Zincsilicafilm 306" 11:06 am (September 30, 2009).

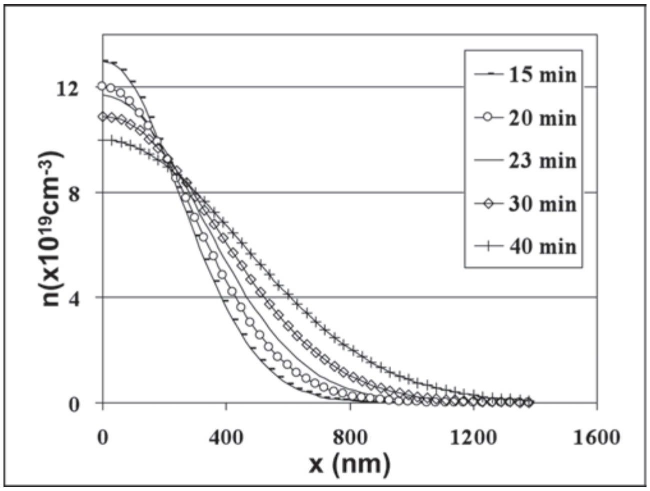

Figure 4: Carrier concentration, n vs. etch depth, x.