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Structural and optical properties of InP layers obtained by plasma-enhanced atomic layer deposition at different temperatures

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Abstract. Plasma-enhanced atomic layer deposition (PE-ALD) was employed to deposit indium phosphide (InP) thin films on silicon substrates at temperatures ranging from 250 °C to 380 °C. Using trimethylindium and phosphine as precursors, the influence of deposition temperature on film growth rate, structural, and optical properties was investigated. A stable growth per cycle (GPC) was observed within the 250–350 °C range, indicating self-limiting ALD behavior, while an increase in GPC at 380 °C suggested onset of non-ideal growth mechanisms. Raman spectroscopy revealed improved crystallinity with increasing temperature, demonstrated by intensified longitudinal optical phonon peaks. Photoluminescence measurements showed near-band-edge emission around 1.36–1.39 eV, with a blue shift and narrowing of the emission peak at higher temperatures, indicating enhanced optical quality and reduced defect density.

Keywords: indium phosphide, atomic layer deposition, plasma, silicon, raman spectroscopy, photoluminescence

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Структурные и оптические свойства слоев InP, полученных методом плазмохимического атомно-слоевого осаждения при различных температурах

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Аннотация. Метод плазмохимического атомно-слоевого осаждения, (PE-ALD), использован для осаждения фосфида индия (InP) на кремниевые подложки при температурах от 250 до 380 °C. Изучено влияние температуры осаждения на скорость роста, структуру и оптические свойства пленок. Повышение температуры приводит к улучшению кристалличности и качеству фотолюминесценции, что указывает на снижение плотности дефектов.

Ключевые слова: фосфид индия, атомно-слоевое осаждение, плазма, кремний, спектроскопия комбинационного рассеяния, фотолюминесценция

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Introduction

Deposition of functional materials by the method of plasma-enhanced atomic layer deposition (PE-ALD) has gained increasing popularity in recent years. The number of different precursors, as well as the number of materials available for this method, continues to grow [1]. One such material is indium phosphide (InP), an AIII-BV semiconductor with a direct band gap of 1.34 eV, making it highly useful for optoelectronic devices such as laser diodes and photonic integrated circuits in the optical telecommunications industry. Atomic layer deposition (ALD) is a critical technique for achieving precise, conformal, and uniform thin-film growth at the atomic scale. PE-ALD further enhances this capability by enabling low-temperature processing and improved film quality, which is essential for temperature-sensitive substrates and advanced semiconductor applications. PE-ALD of InP presents a potential solution by enabling low-temperature, conformal growth, which could facilitate the monolithic integration of InP-based optoelectronics with silicon platforms, opening new possibilities for advanced photonic and electronic systems [2]. This work investigates the PE-ALD of InP using trimethylindium and phosphine as precursors, focusing on the influence of deposition temperature on the structural and optical properties of the resulting films. The findings are aimed at advancing the integration of III–V/Si heterostructures for future photonic and electronic applications.

Materials and Methods

Indium phosphide thin films were deposited on (100)-oriented n-type silicon wafers (double-side polished, 5–10 Ω·cm) using a plasma-enhanced atomic layer deposition (PE-ALD) process. Prior to deposition, the substrates were cleaned in a 10% aqueous hydrofluoric acid (HF) solution to remove the native oxide layer. The deposition process were carried out in an Oxford Instruments Plasmalab 100 PECVD system equipped with a 13.56 MHz capacitive-coupled RF direct plasma source. Trimethylindium (TMI) and phosphine (PH_3), both diluted in hydrogen, were used as the indium and phosphorus precursors, respectively, while high-purity argon served as the purge gas. The plasma was ignited during the PH_3 pulse only, with an RF power of 200 W (power density 440 mW/cm^2). The precursor pulse and purge times were optimized to ensure self-limiting surface reactions and avoid parasitic CVD effects. The deposition sequence are summarized in Table.

In all experiments, the number of ALD cycles was fixed at 400. The substrate temperature was varied between 250 °C and 380 °C to study its effect on the film's growth rate and structural quality. Film thicknesses were measured using a Zeiss Supra 25 scanning electron microscope (SEM). Raman spectroscopy was performed using an Enspectr R532 system equipped with a 532 nm excitation laser to assess the crystallinity of the deposited layers. Photoluminescence (PL) measurements were carried out at room temperature using an Accent RPM Sigma system with an excitation wavelength of 798 nm to evaluate the optical quality of the InP films.

Table

Process parameters

Step	Indium deposition	Purge	Phosphorus deposition	Purge
Precursor	TMI/H_2	Ar	PH_3/H_2	Ar
Pulse time, s	5	10	3	10
Dose, nmol/cm^2	50		2	
Pressure, mTorr	350	0	350	0
RF power, W	0	0	200	0

Results and Discussion

The structural and optical properties of InP thin films deposited by PE-ALD were investigated across a substrate temperature range from 250 °C to 380 °C. In all experiments, the number of ALD cycles was fixed at 400, resulting in film thicknesses ranging from 26.0 to 43.7 nm depending on the growth per cycle (GPC) at each temperature.

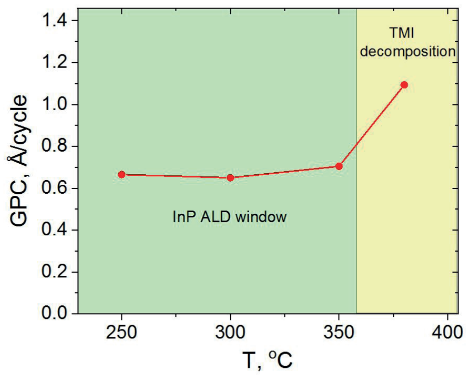

Fig. 1. GPC of InP at PE-ALD process as a function of deposition temperature

These results indicate a relatively stable growth rate in the 250–350 °C range, suggesting operation within the ALD saturation window. The pronounced increase in GPC at 380 °C is likely due to enhanced surface reactivity or partial onset of non-self-limiting reactions at elevated temperature. At these temperatures, partial decomposition of TMI may also occur, leading to an increased growth rate due to monolayer densification and reduced steric hindrance. Figure 2, *a* presents Raman spectra of the InP films deposited at different temperatures. A pronounced longitudinal optical (LO) phonon peak near 345 cm^{-1} is observed for all samples, with increasing intensity at higher temperatures, indicating improved crystallinity. In contrast, broader spectral features and reduced LO intensity at lower temperatures suggest higher structural disorder [3].

Room-temperature photoluminescence (PL) spectra (Fig. 2, *b*), measured using an Accent RPM Sigma system with 798 nm excitation, revealed a strong near-band-edge (NBE) emission in the range of 893–890 nm (corresponding to 1.388–1.393 eV), which is close to the fundamental bandgap of bulk InP. A slight blue shift of the emission peak with increasing deposition temperature – from 893 nm at 250–300 °C to 890 nm at 380 °C – may be attributed to quantum confinement effects in nanocrystalline grains or internal strain in the film [4, 5]. In addition to peak position, the full width at half maximum (FWHM) of the PL signal exhibited a strong temperature dependence, decreasing from 35 nm at 250 °C to 23.2 nm at 350 °C. The narrowing of the emission band indicates an improvement in structural and electronic uniformity, with a reduction in defect-related localized states and nonradiative recombination centers [6, 7]. A slight broadening at 380 °C (FWHM = 24.5 nm) may result from increased surface roughness or grain coalescence at elevated temperatures. These PL results are in good agreement with the Raman data and confirm the superior optical quality of films grown at higher temperatures.

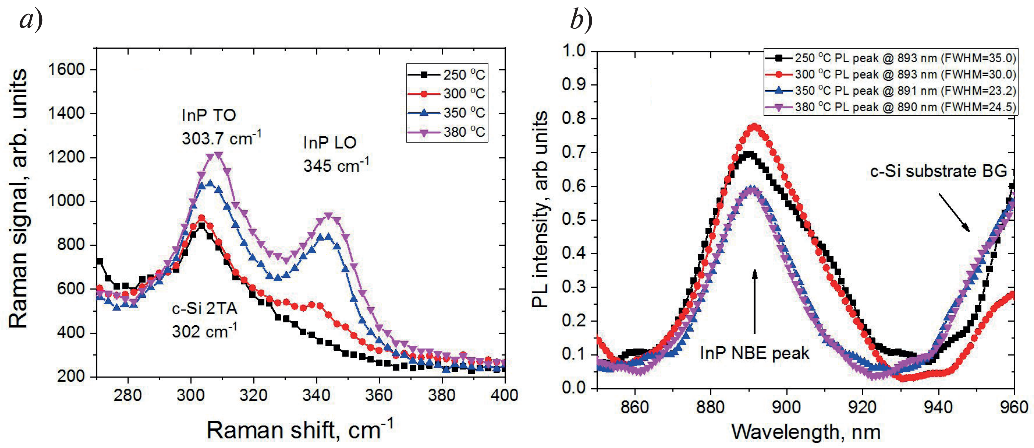

Fig. 2. Raman spectra of PE-ALD InP films deposited at 250 °C – 380 °C (*a*). Room-temperature photoluminescence spectra of InP films (*b*)

Conclusion

Indium phosphide thin films were successfully deposited on silicon substrates using plasma-enhanced atomic layer deposition (PE-ALD) at temperatures ranging from 250 °C to 380 °C. A consistent ALD growth regime was observed at lower temperatures (250–350 °C), with a significant increase in GPC at 380 °C, reaching 1.09 Å/cycle. Structural characterization via Raman spectroscopy confirmed that higher deposition temperatures resulted in improved crystallinity, as evidenced by the intensified LO phonon peak. Photoluminescence analysis revealed near-band-edge emission centered around 1.36–1.39 eV, with a slight blue shift and pronounced narrowing of the emission peak at higher growth temperatures. This behavior suggests enhanced optical quality due to reduced defect density and improved electronic uniformity. These findings demonstrate that PE-ALD enables the low-temperature growth of high-quality InP thin films on silicon, making it a promising method for the monolithic integration of III–V optoelectronic components with Si-based platforms.

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