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ELECTRONIC ENGINEERING

Influence of Ultra-thin GaP Insertion Layer on the Structural of InP Quantum Dots Grown by Solid-source Molecular Beam Epitaxy

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***Abstract*— A systematic study on the effect of GaP insertion layer on the structural properties of InP quantum dots (QDs) was investigated. All samples were grown by conventional solid-source molecular beam epitaxy using a GaP decomposition cell was used as P_2 source for P-based materials. The density of InP QDs directly grown on $In_{0.48}Ga_{0.52}P$ layer was 4.8×10^{10} cm^{-2}, and decreased to 2.4-3.9×10^{10} cm^{-2} on GaP insertion layers which depended on the thickness of GaP layer. The effect of GaP insertion layer on the size distribution of InP QDs was also studied in this work.**

***Keywords*—GaP, InP, $In_{0.48}Ga_{0.52}P$, quantum dots, molecular beam epitaxial (MBE), atomic force microscope (AFM)**

I. Introduction

Self-assembled quantum dots (QD) have been widely applied to laser diodes [1] and high efficiency QD intermediate solar cells (QDSCs) [2]. In particular, in order to achieve the predicted high efficiencies in QDSCs, the QDs must be uniform in size and periodically distributed in all three-dimensions which lead to the formation of an intermediate band or miniband rather than a multiplicity of discrete quantized levels. Stranski-Krastanov (SK) growth mode is the prevalent method for the formation of quantum dots (QDs). The most popular technique of stacked QDs is to take advantage of spontaneous self-assembly of coherent three-dimension island in lattice-mismatched epitaxy. However, this technique usually results internal strain due to misfit dislocation. The lattice mismatch between InP and $In_{0.48}Ga_{0.52}P$ (lattice matched to GaAs) of 3.8% provides sufficient strain to form QDs via the SK mechanism. Advantageous of QD-based optoelectronic devices is the formation of defect-free, ordered arrays of uniform quantum dots, conditions realized in the InP/$In_{0.48}Ga_{0.52}P$ system. Recently, the strained-compensation technique is an approach for an enhancement of quality of multi-stacked layers of QDs [3]. By the first growth interest in nanotechnology, fabrication of regular semiconductor nanostructure with controlled size and height is of great important [4]. InP is a vastly used semiconductor material in the area of visible light source, detector, and solar cell. The size and density of QDs can be controlled by the parameters in the epitaxial growth. These include the substrate temperature, the orientation of the substrate, and rate of incoming speciesm tec. Another method is using the insertion layer to control the sized QDs formed and density [5]. The insertion layer is a different lattice constant with a function of strain-compensated or strain-relaxation. Here, the GaP is used as strain-compensated layer for InP/ $In_{0.48}Ga_{0.52}P$.

In this paper, we report the effect of GaP insertion layer thickness on the height, size and density of InP QDs grown by solid-source molecular beam epitaxy. The QD properties are characterized by atomic force microscopy (AFM).

II. Experimental Details

Quantum dots composed of InP within an $In_{0.48}Ga_{0.52}P$ matrix were elaborated by molecular beam epitaxy on semi-insulating (100) oriented GaAs substrates using a Riber 32P system. The lattice mismatch of 3.8% between InP and $In_{0.48}Ga_{0.52}P$ (lattice matched to GaAs) drives the strain-induced the formation of QDs via Stranski-Krastanow growth mechanism. The growth process was monitored by using 15kV reflection high-energy electron diffraction (RHEED) system. The removal of native oxide was performed by

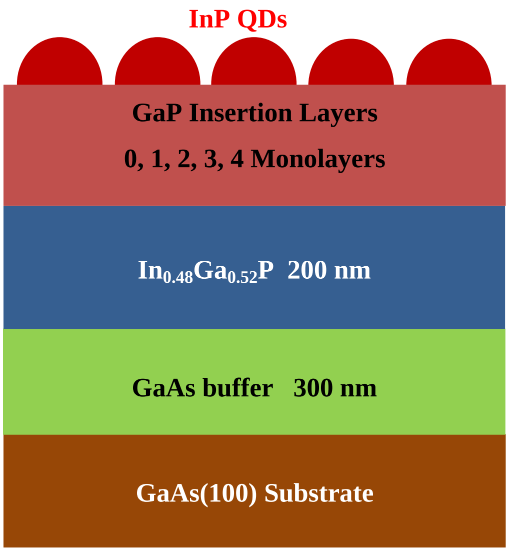

Fig. 1 Schematic representation of InP QDs structure

heating the substrate under As_4 beam at 600°C until the streaky pattern appeared. After oxide desorption, a 300 nm thick GaAs buffer layer was grown at 580°C and followed by a 200 nm $In_{0.48}Ga_{0.52}P$ grown at 480°C. After the deposition of 300 nm GaAs, the growth was interrupted to change from As to P rich ambient. Then, GaP insertion layers with 0-4 monolayers were grown prior the growth of InP QDs. Finally, the QDs were fabricated by deposited 3ML InP with temperature of 450°C at growth rate 0.5 ML/s. The relatively low temperature was chosen in order to inhibit In incorporation from the barrier into the QDs during their self-assembly [6]. The samples were characterized their surface morphology by atomic force microscopy (AFM). Schematic representation of the InP QDs structure with 0-4 ML GaP insertion layer is depicted in Fig. 1.

III. Results and Discussion

A. *Characterization of InP QDs by Atomic Force Microscopy (AFM) technique*

Figures 2 (a)-(e) show AFM images of InP quantum dots grown without and with 1-4 ML GaP. AFM images of five

We note the AFM images of 500×500 nm^2 area that size (diameter), height, uniformity and density of InP QDs. The study of quantum dot formation and distribution of their size and height for different thickness reveals that average height and diameter of smaller (bigger) QDs are 1 nm (6 nm) and 37 nm (56 nm), respectively. Both size and height are increased while increasing the thickness of GaP insertion layer. The surface morphology of InP is also revealed that the insertion of GaP improves the uniformity when the GaP thickness is over 3 ML. The density of all the QDs (smaller and bigger) is in the range of 2-5×10^{10} cm^{-2} [7]. The density of coalesced InP QDs decreases with the increase of thickness of GaP insertion layers. InP QD on $In_{0.48}Ga_{0.52}P$ is the highest density of about 4.8×10^{10} cm^{-2}.

B. *Effect of size and density characteristics of InP QDs*

In order to investigate the role of GaP contamination layer, we perform the characterization of size and height by AFM. Figure 3 shows the size (diameter) distribution of the quantum dots with a various thickness of GaP insertion layer. The lateral size of these structures is increased while increasing the GaP layer thickness. For comparison, the average diameter of

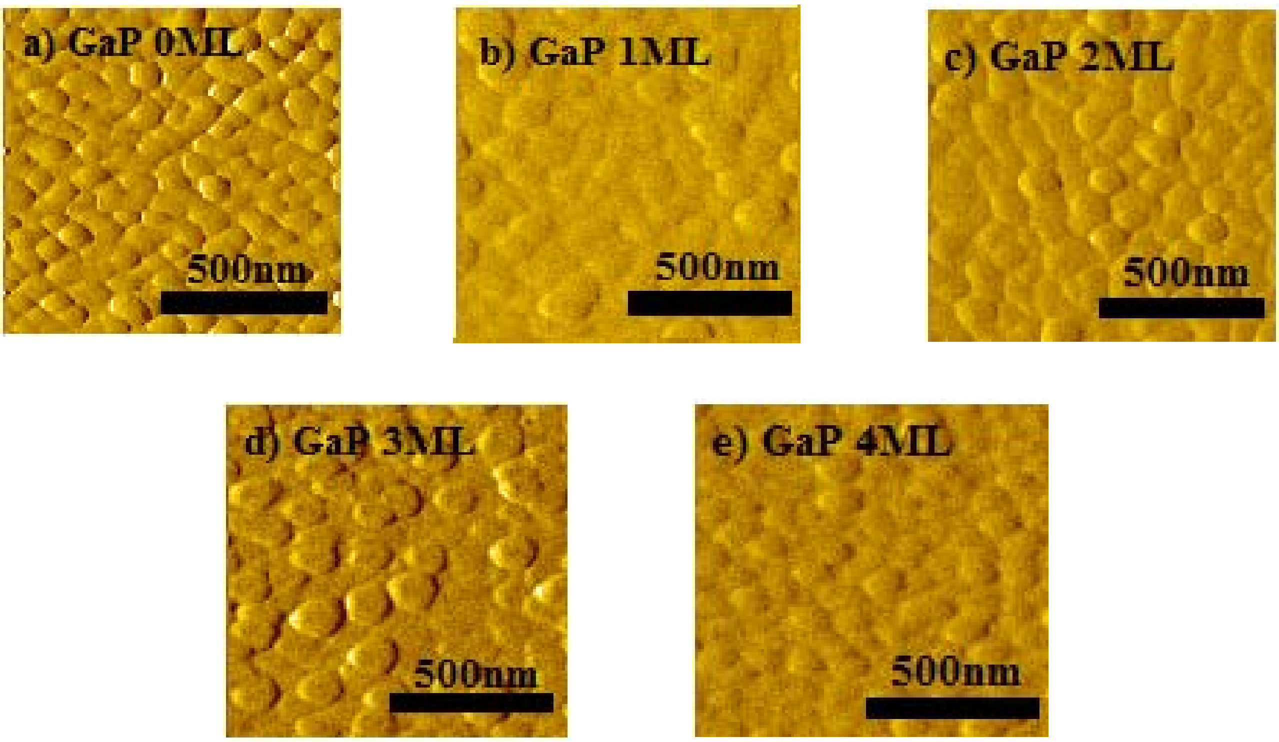

Fig. 2 Typical AFM images of InP QDs on (a) 0 ML (b) 1 ML (c) 2 ML (d) 3 ML (e) 4 ML GaP layers

samples grown at the same growth condition and the same InP coverage of 3 MLs at about 450°C growth observed for all samples with the changes of the thickness of GaP insertion layer.

the sample with 3 ML GaP insertion layer is larger than the other samples at about 52 nm. For sample without GaP layer, the largest dot diameter is about 42 nm and QDs uniformity is good at that condition. The sample with 1 ML GaP layer, the average dots size increases to 45 nm and dots uniformity is declined. For samples with GaP insertion layers thickness of 2 to 4 ML, the average dots size also increases to 45, 49, and 48 nm, respectively and dots uniformity is declined.

However for increasing GaP insertion layer thickness, the size of the quantum dot is increased and the uniformity is declined as shown the regularity of their distributions in Fig 3. The sample of 4 ML GaP insertion layer, the QDs size is not clearly different from the sample of 3 ML GaP layer. Although this may be due to thicker insertion layer, it is likely that most of the extra material comes from the exposed GaP surface through In/Ga exchange which may be further enhanced by strain as As/P exchange [8]. In addition to the indium segregation, the In/Ga exchange reaction affects the

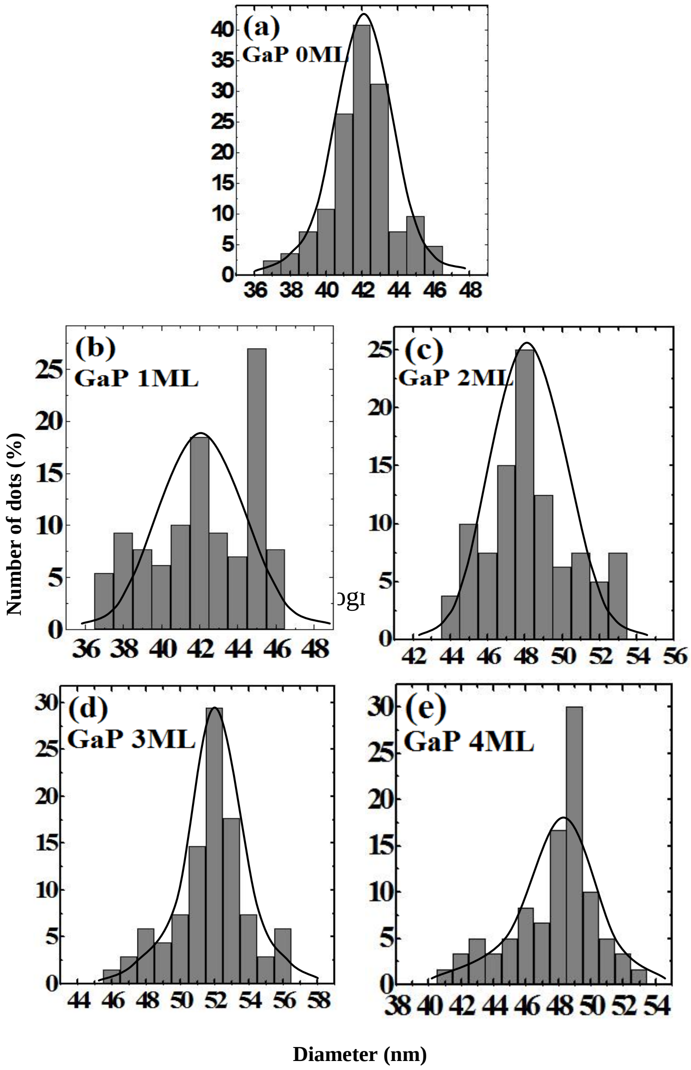

Fig. 3 Size (diameter) distribution histograms of InP QDs on (a) 0 ML (b) 1 ML (c) 2 ML (d) 3 ML and (e) 4 ML GaP layers

indium atoms migrate to the top of dots driven by strain energy to decrease the total system energy and form excess InP QDs nucleation on GaP layer. The exchange reaction occurs at the places through the thin GaP insertion layer which are covered by the dots. The free InP recombining with P atoms. This leads to bigger QDs as noted in the AFM images.

Fig. 4 shows height histograms of InP QDs that extracted from 500×500 nm^2 AFM images. The average height of all samples was nearly the same. A comparison of samples with 0 and 1 MLs of GaP insertion layer, they are the same average height at about 4 nm. The height of 2, 3 and 4 MLs GaP insertion layer samples are slightly decreased. When the thicker GaP insertion layer is grown between QDs and $In_{0.48}Ga_{0.52}P$ layer, the height of the InP QDs increase and the dots become less uniform in terms of size and composition distribution due to suppression of the exchange reaction as noted in the AFM images. The sample without GaP insertion layer showed a significantly improved size, height dispersion and homogeneity. According to the similar effect of QDs

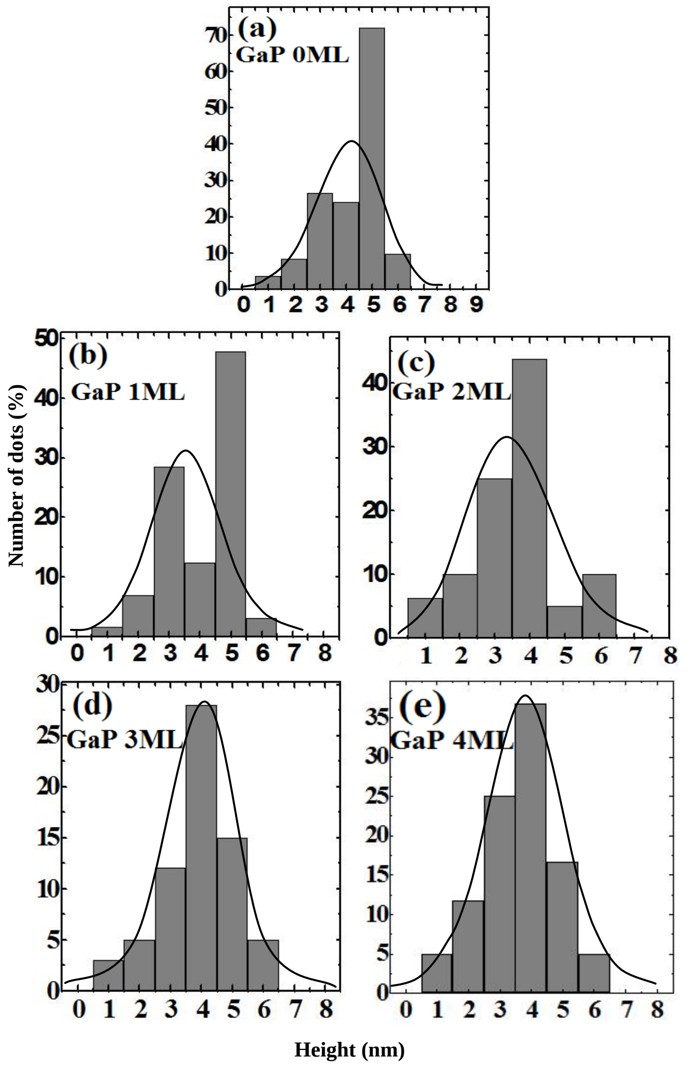

Fig. 4 Height distribution histograms of InP QDs on (a) 0 ML (b) 1 ML (c) 2 ML (d) 3 ML and (e) 4 ML GaP layers

diameter, the segregated indium atom may react with P bond during the growth of InP QDs and forms additional InP which increased the QD height and its non-uniformity. Furthermore, the size and height fluctuation was minimal under the effect of strain compensation layer.

Another important parameter in the growth of semiconductor III-V quantum dots is the dots density. The dot density decreases approximately from 4.8×10^{10} cm^{-2} to 2.7×10^{10} cm^{-2} due to the insertion of 0-4 ML GaP layers. Figure 5 shows the relation of dot density of InP QDs as a function of the GaP insertion layer thickness. It is observed that with increasing GaP thickness, the QDs density decreases and the height and diameter increase [9] as shown in Fig. 5. This is also an expected result and is due to a decreased supersaturation at the onset of nucleation which leads to a lower nucleation density. Since the QDs growth conditions are the same, the bigger QD height and diameter and reduced density for the sample grown directly on $In_{0.48}Ga_{0.52}P$ interlayer indicates that the insertion of the 0-4 MLs GaP layer results in more incorporation of the material. The incorporation efficiency of In during the deposition of an GaP layer reduces as strain increases [10]. The further conclusion is that the density of 3 ML InP QDs depends on GaP thickness because the diffusion length of In atoms on GaP layer is shorten when increasing these parameters [11].

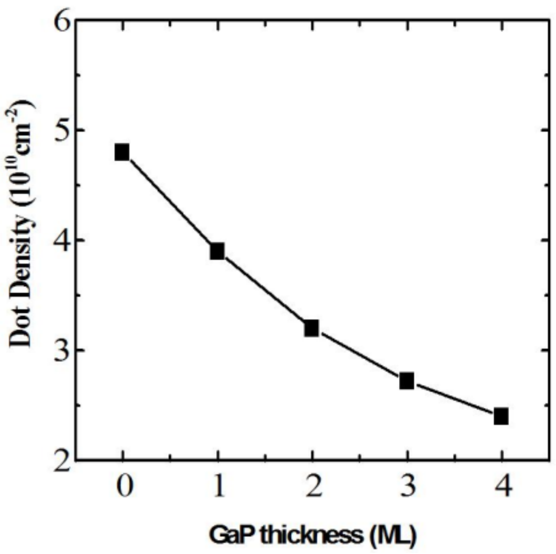

Fig. 5 InP QDs density plotted as a function of 0-4 ML GaP thickness.

Comparing InP quantum dot size (diameter) and GaP insertion layer thickness distribution is shown in Fig. 6. It is note that the quantum dots the average sizes are increased, the GaP insertion layers thickness are increased in samples with 0, 1, 2, 3 MLs and a little bit decrease in sample with 4 ML although growth conditions are the same. This implies that it is due to a difference in the rate of In/Ga exchange during the growth of the quantum dots. Group III exchange during the growth of quantum dots affects mainly the material nucleation through an increase in supersaturation. Therefore, InP quantum dots sizes depend on the thickness of GaP insertion layer at the same growth conditions.

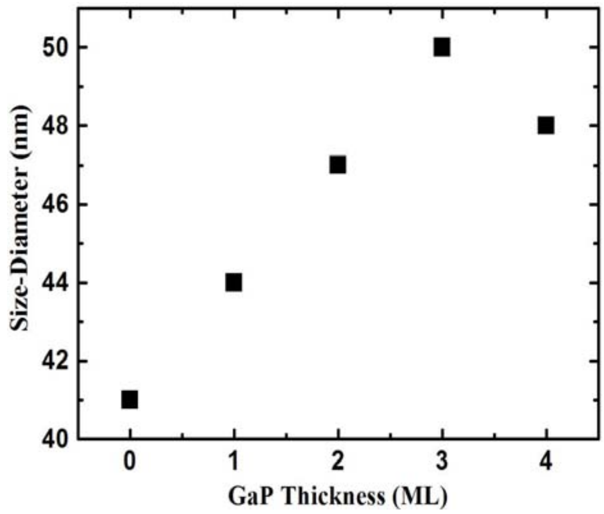

Fig. 6 InP QDs size-diameter plotted as a function of GaP insertion layer thickness.

IV. CONCLUSION

Dependence of GaP insertion layer on structural properties of MBE grown InP quantum dots (QDs) has been studied by atomic force microscopy. The insertion of GaP 0-4 monolayers achieves the large density but it reduces the size and height of QD. A maximum QD density of 4.8×10^{10} cm^{-2} has been achieved at a growth temperature of 450°C with a growth rate of 0.5 ML/s. The Insertion of GaP improves the uniformity when the GaP thickness is over 3 ML.

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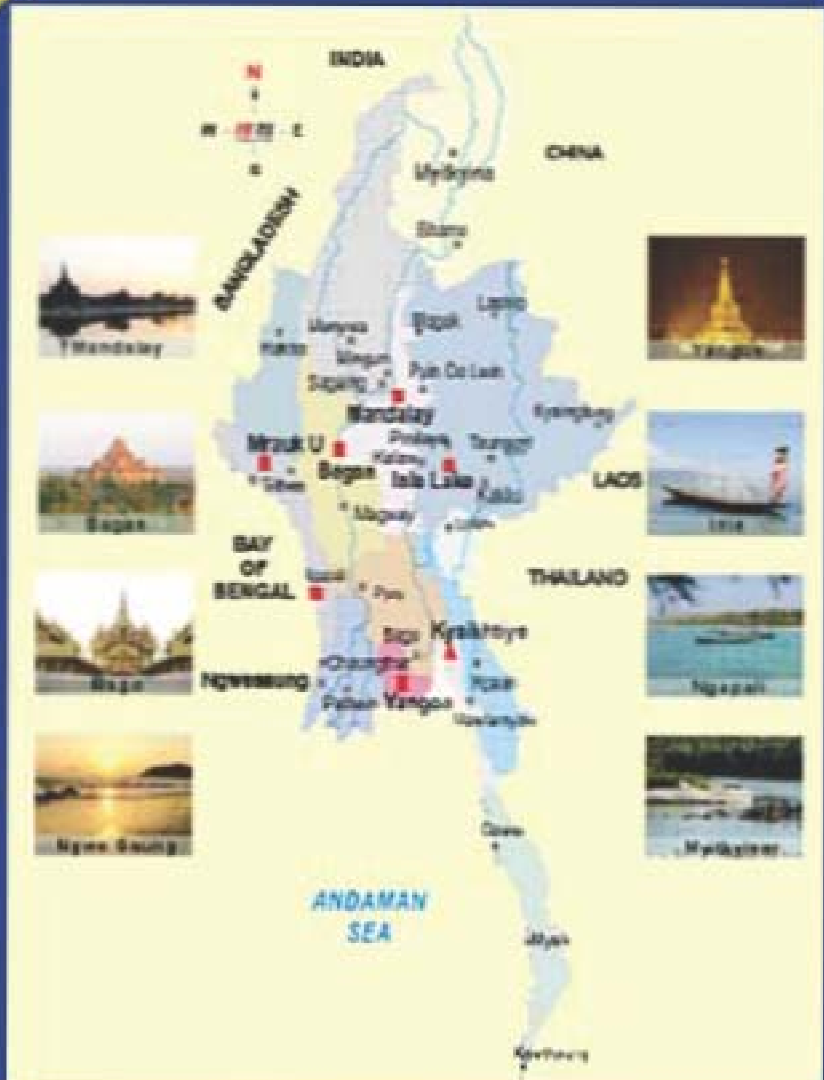

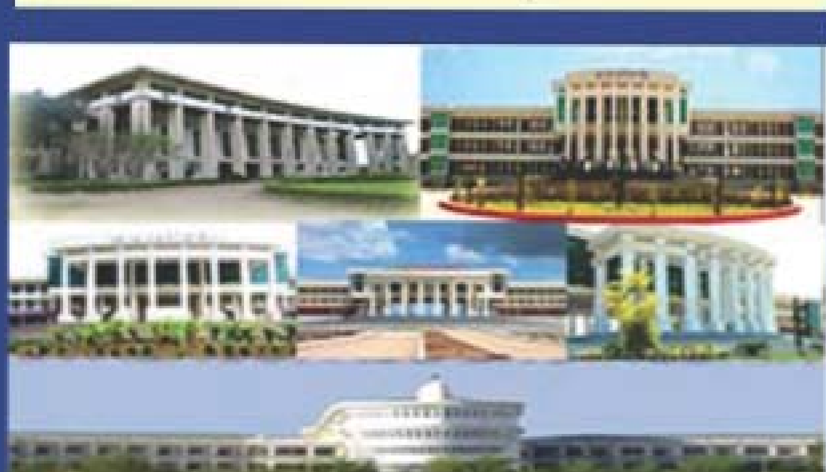

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