Science and Technology of MBE
Room Swan BC - Session ST-MoA1

MBE Technology
Moderator: Paul Simmonds, Boise State University

1:30pm **ST-MoA1-1 NAMBE Innovator Awardee Talk: Physics and Technology of Antimonide Based Short Wave Infrared Avalanche Photodiodes on InP Substrates**, ***Sanjay Krishna***[1], Ohio State University **INVITED**

There are a variety of applications ranging from greenhouse gas detection, 3D topographic mapping and light detection and ranging (lidar) are limited by the sensitivity of the receiver system. In particular, there is a needed for high sensitivity photonic detectors in the short wave infrared (1.5-3 microns) A low noise linear mode avalanche photodiodes (LmAPDs) is a critically enabling component for eye-safe long range LiDAR and remote sensing applications. Unlike PIN diodes, APDs provide internal gain that can lead to increased signal to noise ratio and suppress downstream circuit noise. The highest performing infrared APDs are based on interband transitions in mercury cadmium telluride (MCT, HgCdTe). State of the art (SoA) MCT diodes have large multiplication gains and low excess noise factors due to the favorable bandstructure that promotes single carrier impact ionization. However, their dark currents are high (3-5e-4A/cm2 at a gain of 10 at 125K) that requires cryogenic cooling. Commercial APDs use an InGaAs absorber with an InAlAs or InP multipliers. We are investigating two antimonide based multipliers, AlGaAsSb and AlInAsSb, on InP substrates. We have recently demonstrate GaAsSb/AlGaAsSb separate absorber charge and multiplier (SACM) heterostructures[i] [file:///C:/Users/Yvonne/AppData/Local/Microsoft/Windows/INetCache/Content.Outlook/C2N18W2U/Krishna%20OSU%20NAMBE%20Invited%20Talk%20Sept%202022.doc#_edn1] . We will discuss the technical challenges associated with the design, growth, fabrication and test of these LmAPDs and the potential for the development of these critical APD arrays for active 3D sensing and imaging systems.

[i] S. Lee et al " High Gain, Low Noise, Room Temperature 1550 nm GaAsSb/AlGaAsSb Avalanche Photodiodes", Manuscript under preparation (2022).

2:00pm **ST-MoA1-3 Overview of Virtual Substrate Technologies for 6.3 Angstrom Lattice Constant**, *S. Svensson,* Army Research Laboratory*; N. Mahadik,* Naval Research Laboratory*; G. Kipshidze,* ***Dmitri Donetski****, G. Belenky,* SUNY at Stony Brook

Over the years the approaches to lattice mismatch have ranged from ignoring the problem, to brute force growth of very thick layers, to application of various schemes to engineer a strategy for gradually changing the lattice constant to ideally form a dislocation free virtual substrate (VS) with the desired properties.

A specific lattice constant range of interest is that between GaSb and InSb, in which no other substrate exists, which imposes limitations on our ability to exploit the (Al,Ga,In)(As,Sb) alloy system. This is of great interest primarily because of InAsSb, the III-V alloy with the smallest bandgap among compounds that can be grown with sufficient quality. The minimum energy gap occurs around 6.3 Å, which is why we focus specifically on this value.

InAsSb was set aside in the early 1990's since measurements seemed to indicate that its bandgap was not small enough to reach the long-wavelength infrared wavelength band. The decision was mainly based on investigations of defect-dominated materials. By using a VS approach based on the theoretical work by Tersoff we have been able to improve the quality of InAsSb so that its intrinsic properties could be investigated and the results show a material that closely resembles HgCdTe, the current LWIR performance standard.

Even though our VS approach allows determination of basic materials and device properties, it remains to be determined if it, or indeed any VS, is good enough for large array development. IR detector arrays are some of the largest devices made from semiconductors and are usually sensitive to crystalline defects. The first question that needs to be addressed then is what the density of threading dislocations needs to be. Even for the well-studied case of HgCdTe, there is no publically available information on what density allows what technical application to be addressed, although a general consensus seems to be that a density of 1E5 cm-2 or better is a minimum.

A significant related problem is to find a suitable tool for determining crystalline defect densities at this order of magnitude. However, recent progress in X-ray topology (XRT) is now enabling such investigations. We have been able to apply XRT on thick InAsSb-layers and determine promising defect densities that are close to the target value.

We will further discuss the strategies for designing grades, ongoing programs for modeling VS, summarize the materials properties of InAsSb, compare it with competing materials and discuss other hetero-structures enabled by the VS technique.

2:15pm **ST-MoA1-4 Measurement of Low Semiconductor Substrate Temperatures Using Reflectance Tracking of High Energy Critical Points**, ***Kevin Grossklaus****, J. McElearney, A. Lemire, T. Vandervelde,* Tufts University

Small bandgap semiconductor alloys, including the $Si_{1-x-y}Ge_ySn_x$ and III-V-Bi alloy families, are in development for a range of infrared photonic applications.When produced by molecular beam epitaxy (MBE) these alloys are, out of necessity, grown at low temperatures to ensure Sn or Bi solute incorporation and produce films of good epitaxial quality.Those growth temperatures can be less than 200°C in some cases, far below the optimal epitaxial growth temperatures used for their base materials.Accurate measurement of substrate and buffer temperature before alloy film growth is critical for ensuring film quality and process repeatability.However, measurement is difficult using common non-contact techniques such as optical pyrometry at very low growth temperatures, and difficult for band-edge thermometry in the case of indirect or small bandgap substrates.

In this work we examine in-MBE temperature measurement of some common semiconductor substrates using a reflectance thermometry technique to track above bandgap, higher energy critical points in the dielectric function of those materials.This approach uses a broad spectrum, unpolarized UV-NIR light reflected specularly off the target substrate.The spectrum of reflected light is measured, processed, and then the locations of peaks corresponding to above band-gap critical points are identified in the reflectance data.The locations of those peaks can then be compared to reference reflectance data generated ex-situ at known temperatures, here collected by temperature varying spectroscopic ellipsometry, to determine in-situ process temperature.Temperature measurement by this method is relatively insensitive to background and stray light sources in the MBE system, and by optical system adjustment can be made insensitive to substrate rotation.Data will be presented showing successful temperature measurement of Ge, InAs, and GaSb from approximately room temperature up to or near the higher growth temperatures commonly used for these materials.The sensitivity and accuracy of the technique as shown by this data will be examined.The applicability of this temperature measurement technique to alloy buffer layers, heavily doped substrates, and MBE at cryogenic temperatures will also be discussed.Finally, the shortcomings of the present technique and optical system as employed will be reviewed, with discussion of how those issues may be overcome to enable temperature measurement of other materials, including InSb, InP, GaAs, and Si.

2:30pm **ST-MoA1-5 Perovskite Hetero-Chalco-Epitaxy Enabled by Self-Assembled Surface Passivation and Gas-Source MBE**, ***Ida Sadeghi****, R. Jaramillo,* MIT

Chemical intuition, first-principle calculations, and recent experimental results suggest that chalcogenide perovskites feature the large dielectric response familiar in oxide perovskites, but also have band gap in the VIS-IR and strong light absorption [1]. Preliminary results suggest that chalcogenide perovskites feature excellent excited-state charge transport properties familiar in halide perovskites, while also being thermally-stable and comprised of abundant and non-toxic elements. Nearly all experimental results on chalcogenide perovskites to-date were obtained on powders and microscopic single-crystals. Advances in fundamental

[1] **NAMBE Innovator Award**

understanding and development for applications hinges on the availability of high-quality thin films.

We recently reported the first epitaxial synthesis of chalcogenide perovskite thin films by MBE: $BaZrS_3$ films on (001)-oriented $LaAlO_3$ substrates [2]. The films are atomically-smooth, and scanning transmission electron microscopy (STEM) data show an atomically-abrupt substrate/film interface. The sulfide perovskite film has a pseudo-cubic lattice constant more than 30% larger than the oxide perovskite substrate. This strain is fully accommodated by a remarkable, self-assembled interface buffer layer that enables epitaxial growth of strain-free films, and that the propensity for buffered epitaxy can be controlled by the H_2S gas flow during growth.

We further demonstrate control of the band gap by making layered (Ruddleden-Popper) phases, and by alloying $BaZrS_3$ with Se. We have made the first epitaxial $BaZrS_{(3-y)}Se_y$ films with varying Se composition, up to and including a pure selenide perovskite $BaZrSe_3$. $BaZrSe_3$ is theoretically predicted to be stable in a non-perovskite, needle-like phase with very low band gap. We instead find two distinct phases, which we can control by choice of growth conditions. On non-lattice-matched substrates, $BaZrSe_3$ forms textured films in a hexagonal phase with surprisingly high band gap above 2 eV. On a perovskite $BaZrS_3$ buffer layer, we achieve pseudomorphic epitaxy of $BaZrSe_3$ in the perovskite phase with band gap in the near-infrared. We support these findings with experiments including high-resolution STEM, high-resolution X-ray diffraction, and photocurrent spectroscopy.

This work sets the stage for developing chalcogenide perovskites as a family of semiconductor alloys with properties that can be tuned with strain and composition in high-quality epitaxial thin films, as has been long-established for other semiconductor materials.

[1] R. Jaramillo, J. Ravichandran, APL Materials 7(10) (2019) 100902.

[2] I. Sadeghi et al., Adv. Func. Mater., (2021) 2105563.

2:45pm **ST-MoA1-6 Molecular Beam Epitaxy of Monocrystalline GaAs on Water Soluble NaCl Thin Films***, **Brelon May**,* National Renewable Energy Laboratory*; J. Kim,* Shell International Exploration and Production*; H. Moutinho, P. Walker, W. McMahon, A. Ptak, D. Young,* National Renewable Energy Laboratory

The high cost of III-V substrates for growth can be cost-limiting for technologies that require large area semiconductors. Thus, being able to separate device layers and reuse the original substrate is highly desirable, but many existing techniques to lift off a film from a substrate have substantial drawbacks. This work discusses some of the complexities with the growth of water-soluble NaCl as sacrificial layers for removal of GaAs thin films from GaAs (100) substrates. Much of the difficulty stems from the growth of the GaAs overlayer on the actively decomposing NaCl surface at elevated temperatures. We investigate a wide range of growth temperatures and the timing of the impinging flux of both elemental sources and high energy electrons at different points during the growth. We show that an assortment of morphologies (discrete islands, porous material, and fully dense layers with sharp interfaces) and crystallinity (amorphous, crystalline, and highly textured) occur depending on the specific growth conditions, driven largely by changes in GaAs nucleation. Interestingly, the presence of the reflection high energy electron diffraction (RHEED) beam incident on the NaCl surface, prior to and during GaAs deposition, affects the nucleation of GaAs islands, as well as the resultant crystallinity, and morphology of the III-V overlayer. By utilizing careful exposure of the NaCl to the RHEED beam and a low temperature GaAs nucleation layer, single-crystalline and epitaxial GaAs templates on continuous NaCl layers are realized. The low temperature GaAs layer functions as a template for subsequent single crystalline GaAs homojunction cell deposition by MBE or hydride vapor phase epitaxy. The GaAs cells are removed nearly immediately from the substrate via dissolution of the NaCl layer. However, fusion of as little as a few nanometers of the overlayer to the substrate results in holes that prove detrimental to fabrication of working devices. The frequency of fused locations can be reduced by engineering the early nucleation stages of GaAs on NaCl. Atomic force microscopy between these defects reveals that this process results in an increase in a rms surface roughness of the original wafer of only 0.2 nm. Therefore, combination of these systems could be well-suited for heteroepitaxial liftoff with further reduction of the density of fused locations.

3:00pm **ST-MoA1-7 Thermal Laser Epitaxy of Refractory Metals***, **Lena Nadine Majer**, H. Wang, W. Braun, P. van Aken, J. Mannhart, S. Smink,* Max Planck Institute for Solid State Research, Germany

Thermal laser epitaxy is a promising method for the production of epitaxially grown, refractory-metal layers, which may open up exciting perspectives, e.g., for solid state quantum computing devices. In thermal laser epitaxy, high-power continuous-wave lasers heat both the substrate and the individual evaporation sources, very similar to a MBE process. This method combines the advantages of MBE and PLD, allowing the efficient thermal evaporation and epitaxial deposition of practically any combination of elements from the periodic table, because there are practically no limits on substrate and source temperatures. Our setup has a liquid-nitrogen-cooled shroud, which allows us to grow layers with background pressures below 10^{-10} mbar. Moreover, in many cases crucibles can be replaced by free-standing cylinders of source material, which possibly contain a melt within the solid. Both of these factors allow producing very clean layers with low impurity levels.

We demonstrate and discuss the epitaxial growth of refractory metals on c-plane sapphire. As examples we present and discuss Ru and Ta films. We have optimized the growth parameters to obtain epitaxial films of superior quality, which are apparently devoid of defects over large areas. These films grow in a single phase, with a low surface roughness and an atomically sharp interface between the layer and the substrate.

Science and Technology of MBE
Room Swan A & Sandpiper - Session ST-MoP
Science and Technology of MBE Poster Session

ST-MoP-1 Cryo-MBE: Ultra Low (<20k) Growth Temperatures for High Quality Metal Epitaxy, ***Nils-Eike Weber***, Scienta Omicron, Germany; *D. Beaton,* Scienta Omicron; *M. Heiss,* Scienta Omicron, Germany

Superconductor-semiconductor nanowires enable the route to quantum information devices, like topological qubits [1]. Such hybrid nanowires can be grown in a bottom-up approach by Molecular Beam Epitaxy (MBE). Low-temperature evaporation of the superconductor was demonstrated to promote a continuous and flat film morphology growth and thereby assist the fabrication of disorder-free hardgap superconductor/semiconductor epitaxial hybrids [2]. As pristine surfaces and interfaces are key, eliminating post-growth etch processes by the employment of "shadow epitaxy" is seen as a promising approach [3].

We present a new MBE system that combines an ultra-low temperature manipulator with optimized chamber geometry for shadow epitaxy which enables exploration of so far uncharted growth parameters. The closed-cycle ULT manipulator with base temperature of < 20 K can be precisely positioned in the azimuthal and polar rotation axis allowing defined growth of half-shell or full-shell structures.

Our system and manipulator geometry allows to reach grazing incidence as well as normal incidence for an up to 2" sample cryogenic sample with respect to any of the 10 source ports (including e-beam sources needed for some promising material combinations). This allows to speed up the research of a wide range of possible epitaxial hybrid material systems for a full range of low temperature nucleation conditions. We demonstrate experimental data of the sample temperature at standby as well as when exposed to a hot effusion cell surface as a proof of the excellent manipulator cooling performance.

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[2] P. Krogstrup, N. L. B. Ziino, W. Chang, S. M. Albrecht, M. H. Madsen, E. Johnson, J. Nygard, C. M. Marcus, T. S. Jespersen, Nature Materials 2015, 14, 400.

[3] D. J. Carrad, M. Bjergfelt, T. Kanne, M. Aagesen, F. Krizek, E. M. Fioraliso, E. Johnson, J. Nygard, T. S. Jespersen, Adv. Mater. 2020, 32, 1908411.

ST-MoP-2 Vertical Cation Segregation in During $A_xB_{1-x}N$ Epitaxy, ***Christopher M. Matthews***, *Z. Engel, W. Doolittle,* Georgia Institute of Technology

III-nitrides represent the possibility to realize high efficiency electronics in many different areas, from power electronics to light emitters to photovoltaics and more. However, many optoelectronic devices are limited by indium gallium nitride's (InGaN) tendency to phase separate. Phase separation is one of the key challenges preventing further progress in III-nitride electronics, but the driving mechanisms for this phenomenon are not fully understood. Based on experimental success in limiting phase separation in AlInN and InGaN, we suggest that surface kinetics drive this phase separation during growth, rather than a bulk diffusion mechanism that has traditionally been credited as the cause. We propose that vertical cation segregation (VCS), lateral cation separation (LCS), and thermal decomposition and desorption are the main drivers of phase separation. In this work, we present a comprehensive dynamic growth model to examine the role of VCS in phase separation of ternary III-nitrides, and we compare modeled and experimental films.

A critical dose of excess metal exists for InGaN [1] and AlGaN [2], beyond which diffusion of the larger cation away from the growth surface occurs – a process defined as VCS. Metal-modulated epitaxy (MME) can be used to eliminate VCS or to alter the way VCS manifests in thin films (as compared to metal-rich MBE). VCS can result in self-assembled super lattices (SASL), which are used to evaluate the model presented here. MME's low temperatures and high growth rates can be used to inhibit thermal effects and LCS, respectively, leaving VCS as the lone phase separation driver.

We have built a dynamic growth model to describe the accumulation and consumption of metal adatoms during epitaxy of III-nitrides. These processes are modeled by a system of coupled differential equations that use growth parameters extracted from state-of-the-art III-nitride epitaxy to calculate rates of growth, exchange, decomposition and more. This model is solved numerically to compute the time-evolution of each surface adlayer and a composition profile of the resultant crystalline film. We matched measured XRD to simulated diffraction patterns and composition profiles to TEM for experimental and simulated AlGaN SASLs. The general nature of this dynamic model makes it applicable to most variants of MBE.

References

[1] M. Moseley, B. Gunning, J. Greenlee, J. Lowder, G. Namkoong, and W. Alan Doolittle, Journal of Applied Physics **112**, 014909 (2012).

[2] Z. Engel, E.A. Clinton, K. Motoki, H. Ahmad, C.M. Matthews, and W.A. Doolittle, Journal of Applied Physics **130**, 165304 (2021).

ST-MoP-3 Non-amphoteric N-type Doping with Sn of GaAs(631) Layers Grown by Molecular Beam Epitaxy, ***Alan Cano Rico***, Facultad de Ciencias, Universidad Autónoma de San Luis Potosí (UASLP), Mexico; *L. Espiinosa Vega ,* Facultad de Ciencias, Universidad Autónoma de San Luis Potosí (UASLP). Center for the Innovation and Application of Science and technology, UASLP, Mexico; *I. Cortes Mestizo,* CONACYT-Center for the Innovation and Application of Science and technology, UASLP, Mexico; *R. Pinson Ortega ,* Facultad de Ciencias, Universidad Autónoma de San Luis Potosí (UASLP), Mexico; *F. Perea Parrales,* Center for the Innovation and Application of Science and technology, UASLP, Mexico; *P. Olvera Enríquez,* Center for the Innovation and Application of Science and technology, UASLP, Mexico; *M. Villareal Faz,* Facultad de Ciencias, Universidad Autónoma de San Luis Potosí (UASLP), Mexico; *L. Hernandéz Gaytán , A. Belio Manzano,* Center for the Innovation and Application of Science and technology, UASLP, Mexico; *V. Méndez García ,* Center for the Innovation and Application of Science and technology, UASLP. Facultad de Ciencias, Universidad Autónoma de San Luis Potosí (UASLP), Mexico

The molecular beam epitaxial (MBE) growth and doping of III-V semiconductor compounds on high-index crystallographic orientations (HICO) opens a vast number of possibilities to investigate new physical properties and to develop optoelectronic devices that overcome the currently technology. The peculiar HICO surface anisotropy can conduce to a natural arrangement of unidimensional nanostructures under appropriated growth conditions. Recently, the formation of self-assembled corrugation on GaAs(631) conducted to the formation of 1D multi-quantum well heterostructures, and the modulation of the confined state eigenstates has been achieved, attaining quasi-one-dimensional or fractional dimension eigenstates [1]. Further applications in electrical and optoelectronic devices demand of the realization doped layers preserving the 1D order. Although Si is widely used as an n-type dopant for GaAs (100) the growth of Si doped GaAs on (631)A surfaces results in amphoteric behavior, p-type and n-type conduction depending on the growth parameters [2]. In this work the Sn doping effects on the electronic conduction and optical properties of GaAs(631)A layers grown by MBE are investigated. We found that the conduction type conversion is avoided when Sn-doping is implemented instead. The maximum carrier concentration was $2x10^{19}$ cm^{-3}, which is an order of magnitude higher than previously reported for Si, and it is within the same order of magnitude as compared with the growth of GaAs(100). The electron mobility was $4x10^3$ cm^2/Vs ($1x10^3 cm^2/Vs$) for carrier concentration of $1x10^{17}$ cm^{-3} ($1x10^{19}$ cm^{-3}), suitable for many optoelectronic applications. Raman spectroscopy (RS) of highly Sn-doped (100) samples showed that the TO mode completely dominates the spectrum, indicating low crystalline quality. Conversely, the selection rules for the (631) indicate that the TO mode is allowed, and according to the experimental data it was found to increase with Sn-doping. In general, the incorporation of Sn in HICO-GaAs follows a completely different process as in singular (100)-planes, which was also supported by HRXRD and AFM measurements on the films.

[1] J. Appl. Phys. 128, 244302 (2020); https://doi.org/10.1063/5.0029103

[2] Journal of Crystal Growth 347 (2012) 77–81; https://doi.org/10.1016/j.jcrysgro.2012.03.008

ST-MoP-4 Uniformity: A Phenomenon That Arises from Anisotropy and De-Relaxation During Growth, ***Felipe Perea Parrales***, *C. Mercado Ornelas, A. Belio Manzano,* Center for the Innovation and Application of Science and technology, Universidad Autónoma de San Luis Potosí (UASLP), Mexico*; I. Cortes Mestizo,* CONACYT-Center for the Innovation and Application of Science and technology, Universidad Autónoma de San Luis Potosí (UASLP), Mexico*; L. Vega Espinosa,* Center for the Innovation and Application of Science and technology, Universidad Autónoma de San Luis Potosí (UASLP), Mexico*; D. Valdez Perez,* Instituto de Física, Universidad Autónoma de San Luis Potosí, Instituto Politécnico Nacional, UPALM, Mexico*; C. Yee Rendón ,* Facultad de Ciencias Físico-Matemáticas, Universidad Autónoma de Sinaloa, Mexico*; A. Cano Rico,* Facultad de Ciencias, Autonomous University of San Luis Potosí, Mexico*; V. Mendez Garcia ,* Center for the Innovation and Application of Science and technology, Universidad Autónoma de San Luis Potosí (UASLP), Facultad de Ciencias, Autonomous University of San Luis Potosí, Mexico

Recently, the set of advantages of assembling quasi-one dimensional quantum wire (QWR) heterostructures by molecular beam epitaxy (MBE) over high-indexcrystallographicorientations(HICO)has been exhibited. Some of them include the wave function's in-plane symmetry break, allowing transitions that, in principle, must be forbidden and the induction of blue shifts or red shifts to theQWR energy spectrumdepending on the lateral(L_p)and vertical(H_p) QWRperiodicities(see the inset of Figure 1.(a)). Overall, merging the benefits of both integer-dimension extremes while ruling out their flaws [1], (Figure 1.(a)) and exhibiting the presence of a lateral confinement system(Figure 1.(b)). Although the growth processes over HICO are far from being fully understood, the GaAs (631) has proven to be an ideal substrate to grow QWR heterostructures before, owing to its unparalleled uniformity length [2]. One can assert that until now, there has been scarceor nonexistent *in situ* characterization that could bring us to grasp an overview of the real-time growth process performed over HICOs. This work expands the basis of the GaAs (631) faceting uniformity in terms of the anisotropic diffusion dynamics (Figure 2.(a)) and surface (1x1) buckling-like reconstruction (Figure 2.(b)) together with their dependence on the macroscopic constraints ∏=As/Ga BEP relation and growth temperature. The discussion is supported by experimental results, kinetic Monte Carlo simulations, a proposed inverse W-RHEED method and a thorough reciprocal space analysis. A new perspective for the free energy surface minimization apparatus is introduced.

[1] J. Appl. Phys. 128, 244302 (2020); https://doi.org/10.1063/5.0029103

[2] Applied Physics Letters 101, 073112 (2012); doi: 10.1063/1.4746423

ST-MoP-5 Feature-Independent Molecular Beam Epitaxy Selective Area Regrowth Towards Embedding High Aspect Ratio Microstructures, ***Ashlee Garcia***, *A. Skipper, D. Ironside, S. Bank,* University of Texas at Austin

A molecular beam epitaxy (MBE) approach to selective area epitaxy (SAE) of III-V semiconductors has the potential to advance optoelectronic structures through seamless integration of metals, dielectrics and high-quality crystalline semiconductors. While SAE by metal organic chemical vapor deposition has been widely successful due to its high deposition selectivity, an all-MBE method could enable access to non-equilibrium growth conditions and high layer precision[1,2].

SAE is difficult to achieve with conventional MBE due to III-V nucleation on the amorphous mask. As a result, Allegretti et al. developed periodic supply epitaxy (PSE), a method to inhibit polycrystal deposition by cycling group III deposition under a constant group V flux[2-4]. While an all-MBE approach has enabled the embedding of features 2µm wide and 300nm tall, applications requiring high aspect ratio microstructures such as mid- and long-wave infrared high-contrast photonics[5-7] and aspect ratio trapping of threading dislocations for metamorphic growth[8], are challenging to selectively regrow due to low adatom surface diffusion[1,3].

To expand the accessible applications, a numerical 1D model was developed to describe PSE selectivity and determine selective growth regimes by fitting adsorption, desorption, and diffusion constants to GaAs growth on SiO_2 films at 600˚C [9-12]. The model identified a desorption-limited growth regime under an 18% PSE cycle, in which only thermal desorption off the mask is required to achieve selectivity. The selective growth regime was verified experimentally by observing no polycrystal formation on the mask surface after 100nm of 10% PSE GaAs growth (Ga open 6s, closed 54s) on a SiO_2 film and patterned gratings varying from 1 to 10µm wide, indicating the ability overgrow any arbitrary set of SiO_2 features and motivating its use for embedding high aspect ratio microstructures.

[1] D.J. Ironside et al., *J. Cryst. Growth* (2019). [2] A.M. Skipper et al., 2019 MRS EMC. [3] F.E. Allegretti et al., *J. Cryst. Growth* (1995). [4] S.C. Lee et al. *J. of Appl. Phys.* (2002). [5] Jun Wang *et al.* 2017 *Laser Phys. Lett.* 14125801. [6] C. J. Chang-Hasnain et al. *Adv. Opt. Photon*., Sep 2012. [7] S. S. Wang and R. Magnusson. *Appl. Opt*., May 1993.[8] J.Z. Li et al. Appl. Phys. Lett. 91 (2) (2007). [9] S. Shankar. Diffusion in 1D and 2D, MATLAB. Ret. Apr. 2020. [10] Aseev et al. *Nano. Lett*. (2019). [11] S.C. Lee et al. *Cryst. Growth Des.* 2016. [12] E.M. Gibson et al. *Appl. Phys. Lett.* (1990).

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