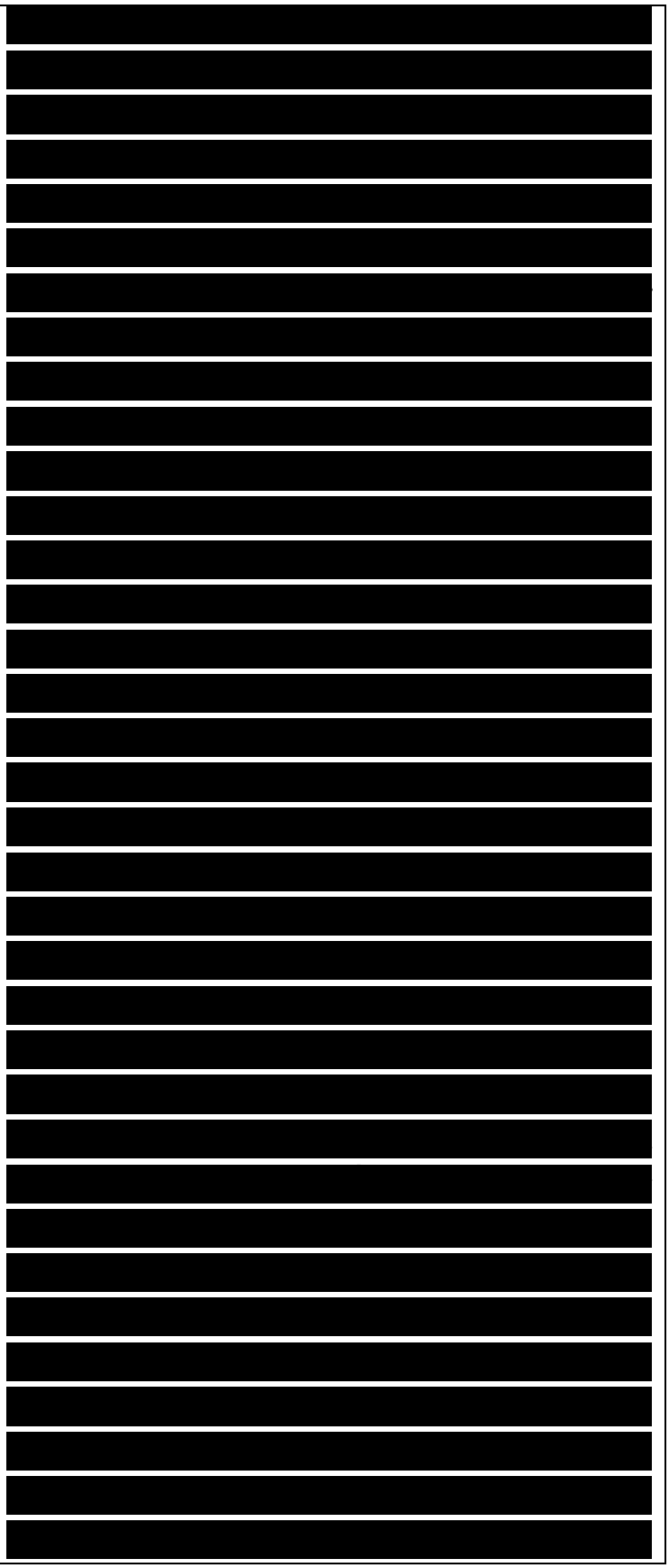
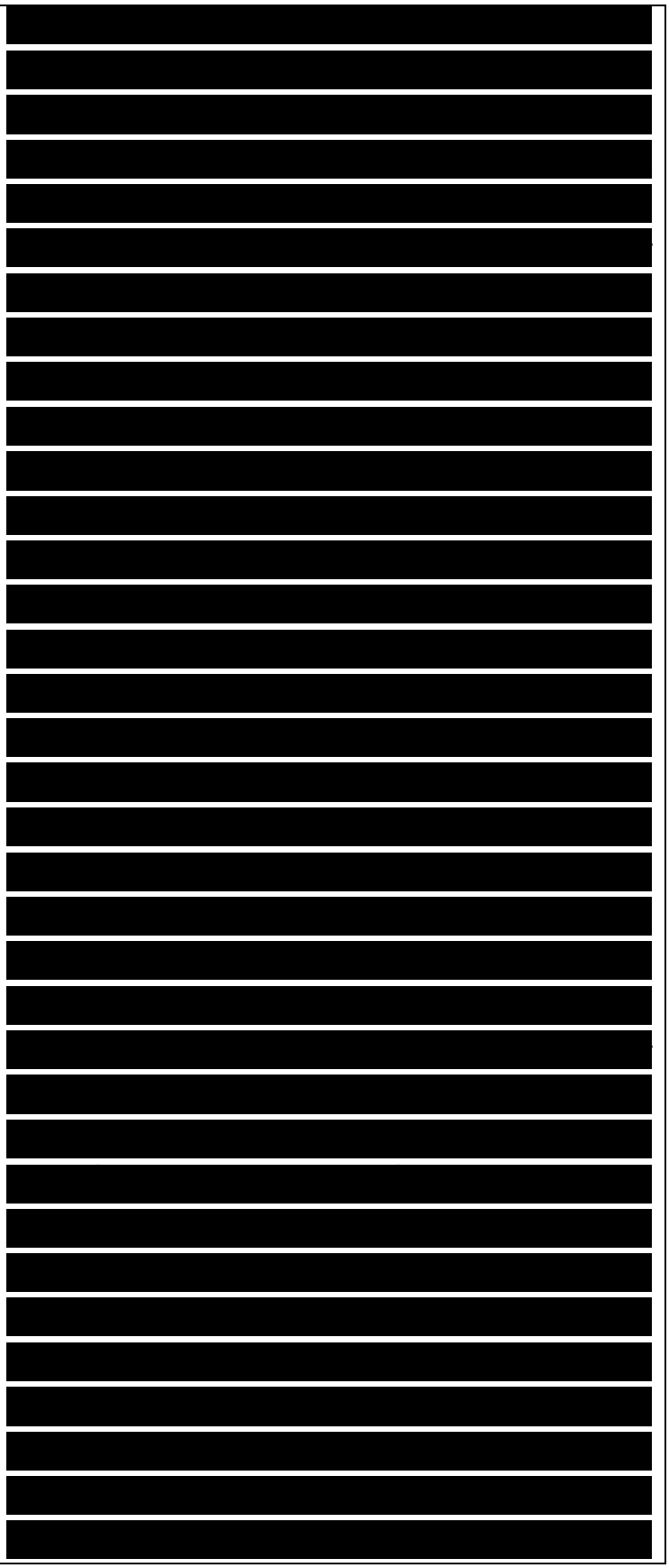
MOLECULAR BEAM EPITAXY: PRINCPLES AND APPLICATION	EPITAXY CHÙM PHÂN TỬ: NGUYÊN TẮC VÀ ỨNG DỤNG checked

However, as growth proceeds, a critical thickness is reached above which strain energy is relaxed through formation of misfit dislocations or the development of three-dimensional islands (Stransky-Krastanov growth mode). This latter phenomenon can be observed for example in SiGe/Si or InGaAs/GaAs growth with high In content and, due to the three- dimensional quantum confinement properties of the resulting islands, has been used to produce self-organized quantum dots. An exhaustive treatment of lattice-mismatched growth can be found, for example, in Ref. [3].	Tuy nhiên, khi quá trình tăng trưởng tiếp tục diễn ra, và đạt đến độ dày tới hạn, trên giá trị này năng lượng biến dạng được giải phóng thông qua sự hình thành các sai lệch mạng hoặc phát triển các ốc đảo ba chiều (mô hình tăng tưởng Stransky-Krastanov). Chẳng hạn như chúng ta có thể quan sát được hiện tượng thứ hai trong quá trình phát triển các lớp SiGe/Si hoặc InGaAs/GaAs với hàm lượng In cao, và do tính chất giam cầm lượng tử ba chiều của các ốc đảo, các cấu trúc này đã được sử dụng để tổng hợp các chấm lượng tử tự lắp ghép. Phương pháp xử lý triệt để quá trình tăng trưởng lệch mạng được trình bày trong nhiều công trình chẳng hạn như công trình [3].
Growth of GaAs-related compound semiconductors. Much of the knowledge we have today about the mechanisms of MBE is due to studies performed on GaAs growth on (001) surfaces. Some of the first fundamental studies have been performed by Foxon and Joice by means of modulated flux mass spectrometry some 25 years ago [10, 11], but their conclusions remain still valid. The recognised process of As2 incorporation (Fig. 9, left) consists in a first-order dissociative chemisorption (hấp thụ cùng với phân ly thành một hoặc nhiều phần) of the physisorbed dimers on surface Ga atoms [10, 11]. By contrast, the incorporation of As4 (Fig. 9, right) involves a second-order, more complicated process: two surface tetramers must meet to generate four chemisorbed As atoms on Ga sites, and a	[redacted]

residual As4 molecule that is desorbed [10, 11]. Therefore, the maximum sticking coefficient is 1 for As2 and 0.5 for As4. Due to the higher As species volatility, with respect to Ga, growth is usually performed with an As/Ga beam flux ratio much higher than one, or two in the case of As4 (this is a general consideration in compound semiconductor growth). This flux imbalance does not affect the one-to-one crystal stoichiometry, since As atoms do not stick if Ga atoms are not available on the surface for bonding. This means that the growth rate is ultimately determined by the Ga atoms flux, since the Ga sticking coefficient is normally one. In fact, only for extremely low As fluxes or high temperatures, outside of the so-called "MBE window" (~580-650°C), significant Ga re-evaporation takes place. Besides, the As sticking coefficient is an increasing function of the Ga flux and, with no Ga flux at all, As does not incorporate on the surface.Fig. 9: Model of GaAs growth from Ga and As2 (left) or As4 (right) [1]Growth of IIIaIIIbV alloys, like AlGaAs, follows the same mechanisms, and an optimal growth window can be found where sticking coefficients of both group-III atoms are unity, with no mutual interference of the two species. The resulting growth rate and composition are simply derived from the two binary growth rates. Things are much more complicated in the case of IIIVaVb alloys: no unequivocal film composition can be derived from the two individual group-V fluxes, since one



species is absorbed more efficiently than the other, and there is mutual interference of the sticking coefficients [12, 13]. GaAs/AlGaAs systems are probably the most standard example of heteroepitaxy in MBE. Since GaAs and AlAs are lattice-matched better than 0.1%, layers of the two materials can be grown in sequence with virtually no thickness limitation for any composition. Besides, interface sharpness is normally not an issue in normal growth conditions. It is important, however, to consider and optimise interface roughness, since this is one of the factors affecting the optical quality of GaAs/AlGaAs quantum wells (QWs) and one of the scattering mechanisms affecting electron mobility in modulation-doped structures (see below). For AlGaAs-on-GaAs growth ("direct" interface), a growth interruption of a few tens of seconds yields a significant smoothing out of the interface (as can be understood by the recovery of the RHEED intensity in the top plot of Fig. 6). For the reverse ("inverted") interface, this is true only for sufficiently low Al compositions, due to the lower mobility of Al atoms (see the bottom plot of Fig. 6). For high Al compositions, growth interruptions do not smooth appreciably the AlGaAs surface. However, in this case, the surface is rough on a length scale (a few atoms) much smaller than the exciton radius (some tens of nm), hence excitons sense an uniform average potential, yielding a relatively sharp luminescence signal [14]. Doping of semiconductors is a fundamental aspect in MBE, since it



allows carrier transport in electronic or optoelectronic devices. In III-V semiconductors, doping can be achieved by using group II (p-type), IV (p- or n-type) and VI atoms (n-type). For p-type doping, elements of the II-b column (Zn, Cd) have a too high vapour pressure at usual growth temperatures, that leaves elements of the II-a column, and Be in particular, as the universal choice. Group- VI atoms are not the most common choice for n-type doping, because of surface segregation and re-evaporation problems [1]. Group-IV atoms are amphoteric, i.e., they can act as donors (if they accommodate on group-III sites) or acceptors (on group-V sites). Among these, C is an acceptor, but has a very low vapour pressure, hence it must be evaporated at very high temperatures (above 2000°C), while the amphoteric behaviour of Ge is difficult to control, and Sn presents a too high surface segregation. Therefore, the universal n-type dopant is Si, as in standard growth conditions on (Ga,In,Al)As (001) it occupies group-III sites, and doping levels up to about 1019 cm-3 can be obtained, before compensation (i.e., substitution of Si on As sites as well) is observed. One problem with Si (and Be as well) is diffusivity towards the surface at doping levels higher than about 2X1018 cm-3, which could be a problem in obtaining sharp doping profiles [15, 16]. In high mobility systems, due to the absence of group-II materials, Si is used as a p-type dopant as well, since it behaves as an acceptor by growing on GaAs(311)A

surfaces in a wide range of growth conditions: it has been shown that bulk doping changes from n- to p-type by increasing the growth temperature above ~430°C, at a V-III ratios near unity [17]. Magneto-transport properties of modulation doped structures.

The incorporation of dopants is a crucial ingredient of the device structures, but also introduces impurities in the lattice. Scattering events with these impurities cause the deterioration of the transport properties of the devices. In bulk semiconductors, the scattering mechanisms are now quite well understood and measured [18]. The scattering mechanisms can be decomposed into five contributions: Optical-phonon scattering; Acoustic-phonon scattering due to deformation potential; Acoustic-phonon scattering due to piezoelectric field; Scattering by ionised impurity; Scattering by neutral impurity. The importance of the various mechanisms is shown in Fig. 10 [19] where the experimental temperature dependence of Hall mobility in n-type GaAs [20] is compared with theory [21]. It is clear that at high temperatures the mobility is limited by phonon scattering whereas ionised impurity scattering dominates at lower temperatures. Fig. 10: Temperature dependence of mobility in n-type GaAs [19]. The dashed curves are the corresponding calculated contributions from various mechanisms [21]. However, at low temperatures the limitation in the mobility can be circumvented by using the method of

modulation doping proposed by Störmer et al. [22]. The idea of this method arises from the use of a structure consisting of two materials with different band-gaps grown one on top of the other. The layer sequence and the band profile for an AlGaAs/GaAs heterostructure is shown in Fig. 11. If the material with larger band-gap (barrier) is doped, in order to maintain a constant chemical potential throughout the two materials, electrons will flow from the barrier (AlGaAs) to the well (GaAs). Due to band bending at the interface, the electrons in the GaAs (well) are confined by an approximately triangular potential near the interface and form a two-dimensional electron gas (2DEG). Usually the dopants are Si atoms, which are placed in the AlGaAs layer and are separated from the interface by an undoped 'spacer' region. Therefore the electrons are physically separated from the ionised Si atoms, hence they are only weakly scattered by these charged impurities. modulation doping .Fig. 11: Layer sequence and band profile of a modulation doped heterostructure. In low dimensional systems, such as AlGaAs/GaAs heterojunctions or quantum wells, the same five mechanisms apply as for the bulk semiconductors. However, there are some other additional ones [23]: Scattering by AlGaAs phonons; Scattering by ionised or neutral impurities located in the barrier material (AlGaAs); Scattering by alloy disorder; Interface roughness scattering; Surface phonon scattering; Intersubband scattering between the quantised levels

in the well. Fig. 12 shows the experimental temperature dependence of the electron mobility in a modulation doped Al0.3Ga0.7As/GaAs heterojunction [24] and the calculated contributions to the mobility from different mechanisms [25]. It is noticed that, unlike in the case of a bulk semiconductor, the mobility does not decrease as the temperature is lowered towards zero as would be expected if scattering by ionised impurities were present. A number of theoretical papers have calculated the mobility in modulation-doped structures from first principles accounting for the above-mentioned scattering mechanisms [25, 26]. Saku et al. [27] have stated that a mobility limit of about 2x107 cm2/Vs in AlGaAs/GaAs modulation doped heterostructures must exist and that the limiting scattering mechanism is due to ionised donor impurities for structures with realistic carrier concentration and optimised spacer thickness. Most models qualitatively describe the experimental results, however, they usually fail quantitatively. The weight of the different scattering mechanisms and the maximum achievable mobility are still under discussion. Fig. 12: Mobility of modulation-doped heterostructures as a function of temperature [25]. Experimentally, a constant improvement in mobility over the years is observed in ultra-pure AlGaAs/GaAs heterojunctions, (see Fig. 13 [28]) where mobilities exceeding 107 cm2/Vs at low temperature have been achieved. The large increase is mainly associated to a

constant improvement of the MBE systems and the purity of evaporation materials. Modified and extremely clean systems are employed for the MBE growth of high-mobility AlGaAs/GaAs heterostructures (see Section 2). Today, only three MBE machines in the world, dedicated to the growth of high-mobility AlGaAs/GaAs heterostructures, are able to produce 2DEGs with low-temperature mobilities around 107 cm2/Vs. Up to now, the world record of 2.29x107 cm2/Vs at T<1K and carrier density n~2x1011 cm-2 was reported in 1999 by the high mobility MBE group at Bell Labs [28]. A mobility of 1.44x107 cm2/Vs at T=0.1K and n=2x1011 cm-2 is published by the MBE group at the Weizmann Institute of Science, Israel [29]. In Europe, the highest 2DEG mobilities (about 8x106 cm2/Vs at 0.3K and n=0.97x1011cm-2 [30], about 1x107 cm2/Vs with n~2X1011 cm-2 [31]) have been reported by the MBE group at the Walter Schottky Institut, Germany. Fig. 13: The mobility in modulation doped heterostructures as a function of temperature and year of fabrication [28]. Recently, experiments were carried out in extremely high-mobility 2DEGs that enabled to distinguish between the main scattering mechanisms that limit the maximum mobility achievable at low temperatures [26]. In optimised 2DEG structures, the dominant scattering sources at low temperature are: remote ionised donors (RI), unintentional background impurities (BIs) in the GaAs and the AlGaAs spacer, and interface roughness (IR). Umansky et al. [29]

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studied μ the μ effect of the spacer thicknesses on the mobility and density of 2DEGs. Fig. 14 shows that the mobility increases as the spacer thickness is increased and saturates thereafter exceeding 107 cm2/Vs for spacer thicknesses in the range of 60-100nm. In order to study the relative contribution of RI scattering they measured a set of structures consisting of a single AlGaAs/GaAs heterojunction, all with a spacer thickness d=72nm, but with different donor densities. As seen in Fig. 15, a linear dependence of the inverse mobility on donor concentration was found, with a maximum extrapolated intrinsic mobility (for number of donors NRI going to zero) of (1.6±0.1)x107 cm2/Vs. By subtracting this value from the measured mobility one can extract the RI limited mobility that fits. RI~(1.1x108)x(1012/NRI) cm2/Vs. In the best structures, with NRI~0.6x1012 cm-2, it results. RI=1.83x108 cm2/Vs, compared to =1.43x107 cm2/Vs. This means that the remote donors were found to be responsible for merely ~10% of the scattering rate. Fig. 14: Mobility (circles) and carrier density (crosses) as a function of spacer thickness[29]. Fig. 15: Inverse of electron mobility for 2DEG samples with different donor concentration (δ-doping sheet density) [29]. In order to distinguish between BI and IR scattering, a single device with a relatively thick (85 nm) spacer was used and the carrier density in the 2DEG was changed via a controlled illumination by an infrared light emitting diode. A

monotonous increase of the mobility with the 2DEG carrier density was observed (see Fig. 16) which is in agreement with previous observations [32] and theoretical predictions for background impurity dominant scattering [26] rather than interface roughness scattering. Furthermore it was found that in the best growth conditions, interface scattering should contribute only for about 5% of the scattering events. Therefore, the authors have concluded that in their best 2DEGs the mobility is limited by background impurity scattering which account for ~90% of the scattering rate.	[redacted]