CHAPTER 1

INTRODUCTION

Over the last decade the new scientific field of metamaterials has grown rapidly. Metamaterials are artificial crystals, whose unit cell sizes and lattice constants are much smaller than the wavelength of the transmitted light. Therefore the optical properties of a metamaterial can be described approximately by effective parameters, as known from classical electrodynamics, like the permittivity ϵ and the permeability μ. For most metamaterials reported so far, the unit cells consist of metal and dielectric structures. By changing the composition of these structures it is possible to tune the effective optical parameters of the metamaterial. This has led to a broad range of new materials with optical properties not known so far in nature. For example metamaterials consisting of arrays of so called split ring resonators can couple to the magnetic field component of an electromagnetic wave and their permeability becomes negative for a specific frequency range. These metamaterials have gained much interest since together with a negative ϵ they exhibit a negative refractive index, as proposed theoretically by Veselago in 1968 [Ves68]. Metamaterials with such novel optical properties have opened the door to a broad range of new physical phenomena, like e.g. cloaking devices [Sch06], superlenses with subwavelength resolution [Pen00, Fan05, Liu07] or inversed Cherenkov radiation [Xi09]. While first pioneering experiments have been performed at microwave wavelengths where metamaterials have structure sizes of several millimeters, experiments have been extended into the near-infrared regime during the last years [Sha05, Dol06]. However, to fulfill the condition of an effective medium, the structure sizes of these metamaterials have to be in the range of a few hundred nanometers and the preparation of such metamaterials becomes quite demanding. Most of the structures prepared by electron-beam lithography (EBL) or focused-ion beams (FIB) are two dimensional, i.e. they do not extend in the direction of the wave vector of the transmitted light. Only few methods like direct laser writing or successive EBL and spin-on glass methods have realized the fabrication of three-dimensional metamaterials [Val08, Liu08] for the near-infrared regime.

In this work the preparation of metamaterials made of rolled-up metal/semiconductor microrolls was established. Expanding the selfrolling mechanism of semiconducting nanolay ers [Pri00] to metal/semiconductor systems allows the fabrication of three-dimensional metamaterials with a high control of layer thicknesses [Sch09]. After describing the concept of the rolling-up process in chapter 2, a rolled-up three-dimensional metamaterial for the visible and near infrared is discussed in chapter 3. This metamaterial consists of a rolled-up superlattice of metal and semiconducting layers. The superlattice exhibits a permittivity which is highly anisotropic in directions parallel and perpendicular to the layers. A promising application of these structures are so called hyperlenses. Hyperlenses allow imaging of objects with a spatial resolution well below the Abbe limit, which limits the resolution of conventional far-field microscopes to about half the wavelength of the scattered light [Abb73]. To determine the optical properties of the rolled-up superlattices reflection and transmission measurements were performed. For the latter measurements a nanosized light source was developed, which could be inserted into the microroll by a special microscope-manipulation setup. We could show by these measurements that the permittivity of the rolled-up superlattices exhibits a metallic dispersion with a characteristic plasma frequency ω_p. By means of finite difference time domain simulations we revealed that rolled-up superlattices with the measured optical parameters are expected to exhibit hyperlensing at ω_p [Sch09]. The position of ω_p, i.e. the operating frequency of the hyperlens, could be tuned by varying the ratio of layer thicknesses of the superlattice. To observe subwavelength imaging through the rolled-up hyperlens first near-field scanning microscopy measurements were performed in cooperation with the University of Bourgogne.

Another concept to realize metamaterials by metal/semiconductor microrolls is discussed in chapter 4. Now, the metamaterial is defined by an array of many rolled-up microrolls. We show with numerical simulations that such a metamaterial exhibits a negative permeability at wavelengths in the far-infrared regime. The preparation of the arrays as well as first transmission measurements with a Fourier spectrometer are presented. Chapter 5.1 summarizes all results obtained so far and gives a short outlook to further experiments, which can be performed in the future.

CHAPTER 2

PRINCIPLES OF ROLLED-UP NANOTECH

The rolling up of nanolayers into micro- and nanorolls was first demonstrated by Prinz et al. [Pri00]: Strained bilayers minimize their strain energy after lift off from the substrate by rolling up into microrolls. Different material systems can be used for the strained bilayers, like strained semiconducting films [Pri00, Sch01, Sch05], or, as shown recently, strained polymer nanomembranes [Mei09]. In our work microrolls consisting of metal and the III-V semiconductors (In)GaAs were prepared. The principle is shown in figure 2.1: A thin metal film is evaporated on top of a semiconductor layer system grown by molecular-beam epitaxy (MBE). All samples were grown by Dr. Holger Welsch and Andrea Stemann in the group of Professor Dr. Wolfgang Hansen. The layer system consists of an AlAs sacrificial layer on top of a GaAs substrate and a strained bilayer of $\mathrm{I}n_x\mathrm{G}a_{1-x}\mathrm{As}$ and GaAs. The GaAs substrate and the AlAs layer have almost the same lattice constant of 0.55 nm and 0.56 nm, respectively [Ada85]. The lattice constant of the $\mathrm{I}n_x\mathrm{G}a_{1-x}\mathrm{As}$ layer in the relaxed state is larger than for AlAs and can be approximately calculated by the concentration-weighted average of the lattice constants of InAs and GaAs [Veg21, Woi96]:

$$d(In_xGa_{1-x}As) = 0.61\,x + 0.56\,(1-x) \tag{2.1}$$

Depending on the Indium concentration, one has to distinguish between different growth mechanisms of the $\mathrm{I}n_x\mathrm{G}a_{1-x}\mathrm{As}$ on top of the AlAs, as shown in the phase diagram in figure 2.2 [Mat74, Hey01, Wel07]. For Indium concentrations $x < 0.4$ and layer thicknesses $d < d_{crit}$ the $\mathrm{I}n_x\mathrm{G}a_{1-x}\mathrm{As}$ grows pseudomorphically, i.e. the lateral lattice constant of $\mathrm{I}n_x\mathrm{G}a_{1-x}\mathrm{As}$ is adapted to the lattice constant of AlAs. This leads to strain inside the $\mathrm{I}n_x\mathrm{G}a_{1-x}\mathrm{As}$ layer. Above a critical thickness d_{crit} the strain is released into misfit dislocations [Mat74], while for an Indium content $x > 0.4$ quantum dots are formed by the so called Stranski-Krastanov growth [Str39, Hey01]. Typically the In_xGa_{1-x}As is grown pseudomorphically to maximize the strain stored in the multilayer to be rolled up.

After the removal of the AlAs sacrificial layer, which is typically done be selective etching with hydrofluoric acid [Hjo96], the strained In_xGa_{1-x}As/GaAs bilayer and the metal film can minimize their strain energy by up-bending and forming a microroll. The radius r of the microroll is determined by the growth parameters and can be calculated approximately by a model of Tsui and Clyne [Tsu97]:

$$\frac{1}{r} = \frac{6(1-\nu)\, E_1 E_2 h_1 h_2 (h_1 + h_2)(a_2 - a_1)/a_1}{E_2^2 h_2^4 + 4E_1 E_2 h_2^3 h_1 + 6E_1 E_2 h_2^2 h_1^2 + 4E_1 E_2 h_2 h_1^3 + E_1^2 h_1^4} \tag{2.2}$$

where ν is the Poisson ratio of In_xGa_{1-x}As and $a_{1/2}$ are the lattice constants, $E_{1/2}$ the Young's moduli and $h_{1/2}$ the thicknesses of the strained (In_xGa_{1-x}As) and unstrained layers (GaAs/metal), respectively. This model was established originally only for epitaxially grown monocrystalline layers. To include the influence of the evaporated, polycrystalline metal film into this model we approximate the unstrained GaAs/metal layer by a pure GaAs layer of equal thickness. This approximation neglects the additional strain induced by metals with high melting temperatures (e.g. chromium) and differences in elastic properties of the metal and the GaAs [Sch05, Tho89]. However, for our structures the measured microroll radii were in good agreement with the theoretical values using the above approximations.

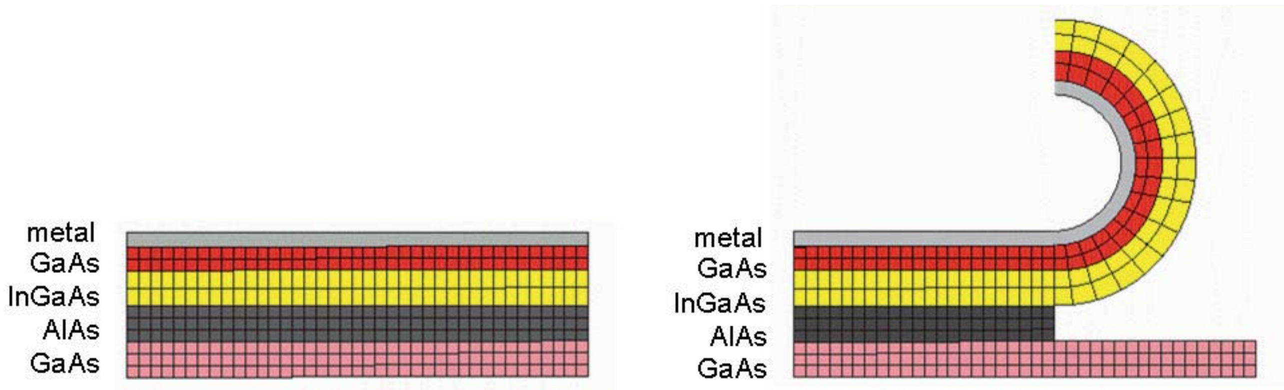

Figure 2.1: Principle of the roll up process of a strained metal/(In)GaAs bilayer into a microroll.

By rolling up metal/semiconductor layers into microrolls, three-dimensional metamaterials, which are periodic in the radial direction, can be prepared in a single step. In our experiments large arrays of microrolls with only one rotation (chapter 4) as well as multirotated microrolls (chapter 3) were prepared. The specific preparation steps for each type of metamaterial will be discussed in detail in the corresponding chapters.

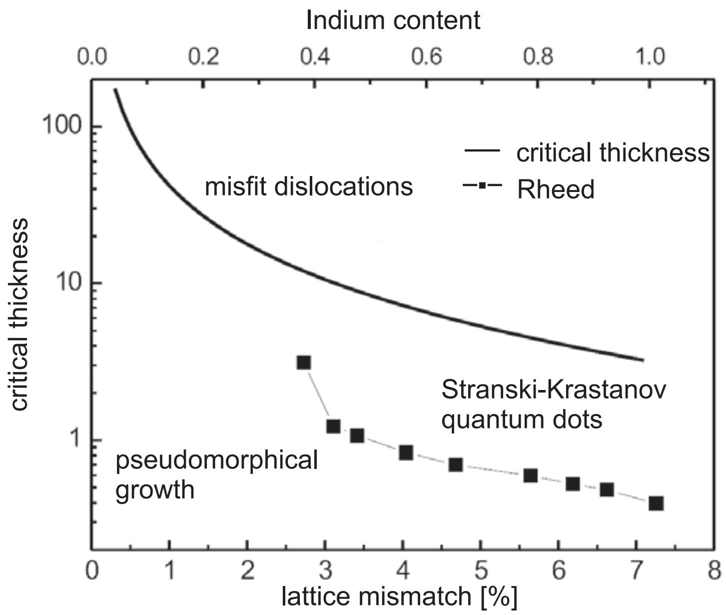

Figure 2.2: Phase diagram for the epitaxial growth of strained $In_xGa_{1-x}As$ on $AlAs$. The solid line shows the theoretical curve for the critical thickness with respect to lattice mismatch and Indium content [Mat74]. The phase boundary for Stransky-Krastanov growth (black points) was experimentally measured by Christian Heyn [Hey01].