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GaN-BASED PHOTOCATHODES FOR HIGH BRIGHTNESS ELECTRON BEAMS

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Abtract

Prospective light sources require photocathodes with high quantum efficiency (QE), long lifetime and minimized thermal emittance. One promising candidate meeting the aforementioned specifications is gallium nitride (GaN). Due to its wide band gap (E_g = 3,4 eV), GaN can be excited by UV-light sources. Its thermal and chemical stability are added bonuses [1-3]. In the framework of the present activity, the synthesis of GaN films on copper, niobium, tantalum, molybdenum and silicon (Si) by means of RF magnetron sputtering is proposed. In this context, gallium (Ga), gallium arsenic (GaAs) and GaN are suitable source material candidates, which are sputtered in a Nitrogen (N) and Argon (Ar) plasma discharge. The conductivity as well as the band gap (E_g) of the corresponding films can be modified by dopants like magnesium (Mg) and indium (In), respectively [1, 3]. Standard materials science characterization techniques such as SEM, EDX, XRD or XPS are used to explore the growth mechanism of GaN alongside with a morphological and chemical examination. To assess and optimize the performance of the photocathode the abovementioned requirements are tested in an in-situ setup. Hence, the coating chamber is connected with a contamination chamber for the QE measurement to transfer the synthesized GaN films under UHV conditions. Following, a project outline, first experimental results of GaN films, synthesized based on a GaAs source sputtered in a pure N_2 plasma discharge are presented.

INTRODUCTION

Superconducting radiofrequency photoinjectors (SRF gun), which are for instance operated at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) and Helmholtz-Zentrum Berlin (HZB), require photocathodes providing high brightness electron beams. In addition, a high current and operating in a continuous wave mode are required. Hence, photocathodes with high QE, long life time, minimized thermal emittance as well as reduced dark current are necessary. One promising candidate meeting the aforementioned specifications is GaN [1-3]. Due to its wide band gap (E_g = 3,4 eV), GaN can be excited by UV-light sources, which are used e.g. at HZDR.

The thermal and chemical stability of GaN are added bonuses. In the framework of the present activity, GaN films are synthesized and subsequently modified. As shown in the schematic band diagram in Figure 1, for undoped and non-modified GaN, there is a high potential barrier. Accordingly, the vacuum energy level (E_{vac}) is higher than the conduction band energy level (E_c) whereby excited electrons can not leave the surface of the film [2].

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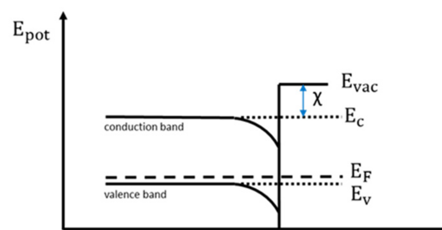

Figure 1: Schematic band diagram of non-modified GaN [2].

By p-type doping with Mg, the diffusion length of the excited electrons within the bulk material can be increased. Hence, generated holes are drifting to energetically favourable surface locations and the emerging electric field causes a bending of the band gap. However, after p-type doping, E_{vac} is still higher than the E_c. Hence, another preparation step is required.

To achieve a negative electron affinity (NEA), the film surface can be activated by a Cs deposition [1-3].

$$NEA = E_{vac} - E_c < 0 \quad (1)$$

Accordingly, electrons of the adsorpt Cs-atoms diffuse to unsaturated surface atoms, where an electric dipole occurs. The excited electrons can tunnel through a small potential barrier and leave the film surface (Figure 2) [1, 2].

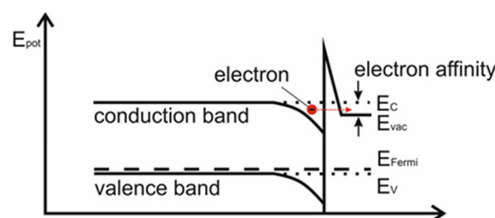

Figure 2: Schematic band diagram of GaN after Cesium deposition [1, 2].

After the preparation, the films will be characterized in situ, to correlate their QE with the preparation parameters. QE is defined as the ratio of incident photon to emitted electron, described by the photoelectric effect (Figure 3). For the emission of an electron, the GaN film is excited by a light source, where the energy of the absorbed photons needs to be higher than E_g.

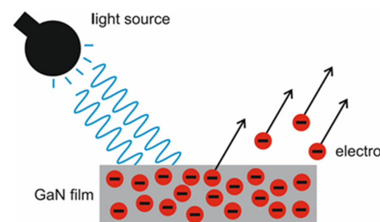

Figure 3: The main principle of the photoelectric effect.

Finally, semiconductor photocathodes exhibit a higher QE compared to those composed of metal. Disadvantages are a lower lifetime and the contamination risk of the SRF gun [4]. Consequently, alongside with achieving a high QE and improving the lifetime, the adhesion of the GaN films are in focus of this research.

EXPERIMENTAL

The preparation includes the synthesis of GaN films by RF magnetron sputtering and a subsequent modification by reactive ion etching (RIE). GaN is a semiconductor material and therefore it can not be synthesized by DC sputtering. By using RF magnetron sputtering, target-charging is avoided by an alternating potential. Hence, the positive ions of the sputtering gas are accelerated to the negatively charged. target and the Ga-atoms will be sputtered. N_2 (99,999 %) as a reactive gas, Ar (99,999 %) as an inert gas or a mixture of both gas types will be used as the sputtering gas. The sputtered Ga-atoms forming a GaN thin film. Potential target materials are Ga, GaN and GaAs. Due to the low melting point of pure Ga ($T_m \approx$ 29.8 °C), it is not possible to sputter it from the solid phase as usual. To avoid impurities within the film, high purities are required for the sputtering source, which is difficult to obtain for GaN. In contrast, the challenge for GaAs is, to synthesize films without any As-content. Potential substrates are copper, niobium, tantalum, molybdenum and Si.

To increase the adhesion between film and substrate and consequently avoiding the contamination risk of the SRF gun, an interlayer can be applied [3]. Potential interlayers are e.g.: aluminum nitride or zinc oxide. To quantify the adhesion, scratch-tests and nanoindentation will be applied by a Hysitron Triboindenter system.

For the excitation at different wavelengths (e.g. SRF gun at HZDR or HZB), E_g can be modified by adding In or Al. Indium decreases E_g and the photocathode can be driven by a light source in the visible range, whereas aluminum increases E_g.

For the realization of the abovementioned requirements, the coating chamber is equipped with four different sputtering targets (e.g.: Ga- and interlayer source, Mg and In). The used experimental setup is shown in the scheme of Figure 4. To avoid any contamination inside the UHV coating chamber (B), a loading chamber (A) is applied. After evacuation of (A), the sample will be transferred under UHV conditions to (B). To assess and optimize the performance of the photocathode, the QE will be measured in-situ after the synthesis of the films. Therefore, the sample will be transfered to preparation and measuring chamber for the Cs-activation and subsequent QE-measurement (D). Eventually, the SEY of all involved materials can be characterized in the SEY-setup (C) to draw a more complete picture of the whole system.

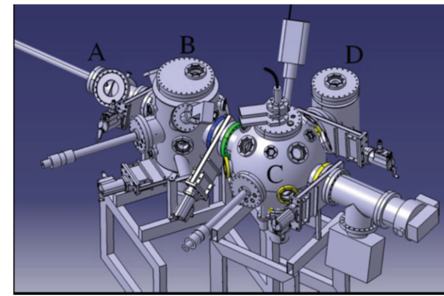

Figure 4: Scheme of the experimental setup: loading chamber (A), coating chamber (B), SEY-measurement (C) and QE-measurement (D).

In case of the in-situ QE measurement, a new setup is established. The QE at a certain wavelength (λ) is calculated with equation 2:

$$QE\ (\lambda) = \frac{N_e}{N_\gamma(\lambda)} = \frac{h \cdot c}{q_e} \cdot \frac{I}{\lambda \cdot P_{light}(\lambda)} \tag{2}$$

For the calculation of the QE, the photoelectric current (I) and the light power (P_{light}) are measured successively at the different wavelengths of interest. The band gap of pure GaN is E_g = 3,4 eV (@ 300 K) with the associated wavelength λ = 364,7 nm. As mentioned above, E_g and with it λ will be modified by adding In or Al. Due to the different required excitation wavelenghts, a combination of a Deuterium- (λ_{range} = 200 – 400 nm) and a Xenon (Xe) light source (λ_{range} = 400 - 1100 nm) is applied. The output of the Deuterium lamp at lower wavelengths is higher compared to the Xe lamp. At higher wavelengths the Xe lamp delivers higher intensities and irradiance. Therefore, an improved signal to noise ratio over a wide range of wavelength can be maintained. For light power measurement, a thermal sensor and a Si-photodiode is used. Both have typical advantages and disadvantages. With the thermal sensor, a broad spectral- (0,19 – 25 µm) and power range (100 µW – 2 W) are measurable.

However, the thermal sensor is sensitive to ambient temperature changes and has a high response time (≈ 3s). In contrast the photodiode has no response time and a lower power range (500 pW – 0,5 mW) can be measured. The driving light source has a normal angle of incidence. Emitted photoelectrons are detected by a ring shaped Cu anode in the near vecinity of the sample. The photoelectric current is measured by a current amplifier. A bias Voltage up to 1000 V is applied to the sample to ensure that the measurement is not affected by space charging effects. The measurement range is between 100 aA – 20 mA, with a resolution of 10 aA. The basic principle of the QE measurement is shown in the scheme of Figure 5.

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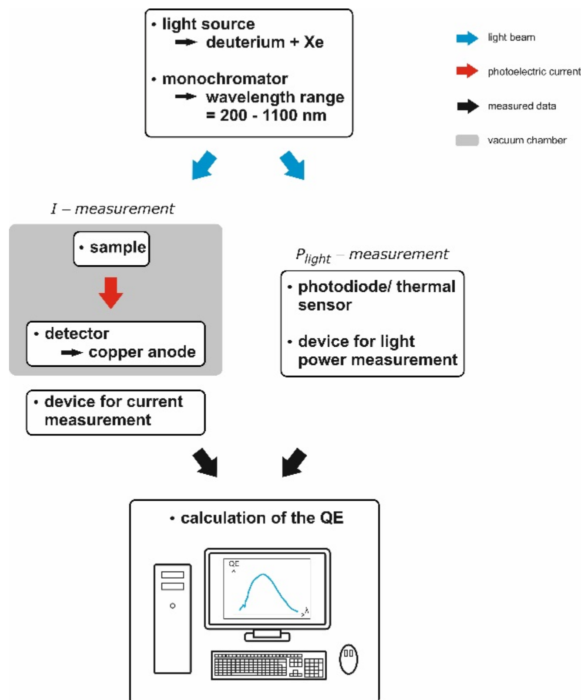

Figure 5: Scheme of the QE measurement.

For the first experiments GaN films have been synthesized on Si (111) using a high purity GaAs target (99,9999 %,) sputtered in a pure N_2 plasma discharge. The Si wafer were cleaned with ethanol and distilled water in an ultrasonic bath prior the deposition. The substrate temperature (RT – 800 °C) and the N_2 pressure (0,2 – 1,6 Pa) are varied, to examine their influence on the crystal growth and structure of the films. A RF power of 100 W is applied during the deposition for one hour. The cross section and the surface of the films are investigated by using a SEM, typ: ZEISS Model Ultra 55. The Arsenic content of the films have been determined by using EDX. The crystal growth have been elucidated employing a PANalytical x-ray diffractometer equipped with a Cu anode.

RESULTS AND DISCUSSION

The cross section of a GaN film, synthesized at 800 °C and 0,4 Pa, is shown in Figure 6. Film thickness is about 400 nm for all films under investigation and a collumnar growth is visible. The surface of a GaN film, synthesized at 800 °C and 0,4 Pa, is shown in Figure 7. A polycrystalline texture with a small grain size between 10 and 20 nm is visible.

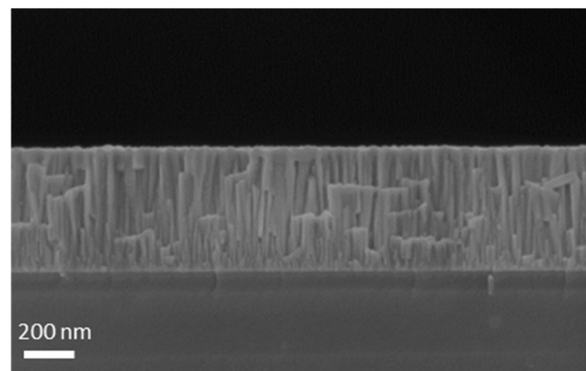

Figure 6: Cross section FESEM image of a GaN film synthesized at 800 °C and 0.4 Pa.

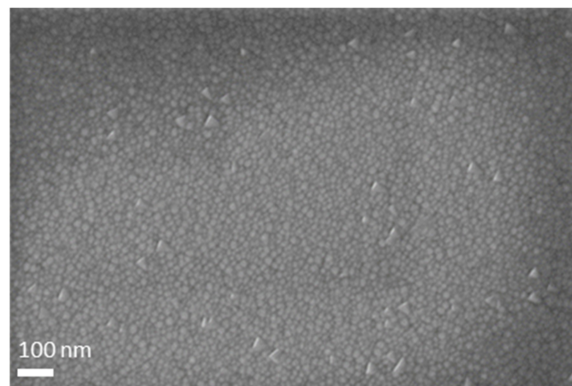

Figure 7: Polycrystalline surface texture FESEM image of a GaN film synthesized at 800 °C and 0.4 Pa.

By means of the EDX measurement it can be seen that that the As content within the GaN films decreases with increasing substrate temperature (figure 8). However, within the parameter range applied so far it is not possible to synthesize GaN films without As content by using a GaAs target.

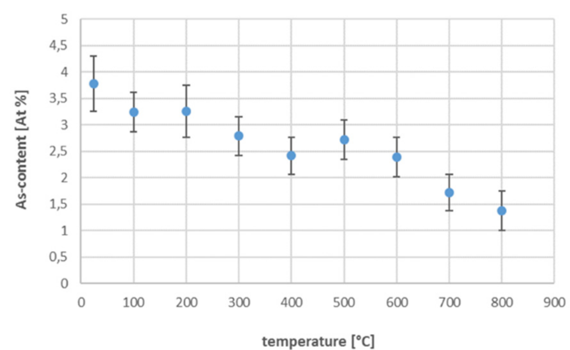

Figure 8: EDX measurements to examine the dependence of the As content within the GaN films referring to the substrate temperature.

The crystallinity of the films depends on the substrate temperature and the N_2 pressure during the synthesis, as shown in the XRD patterns of the Figures 9 and 10.

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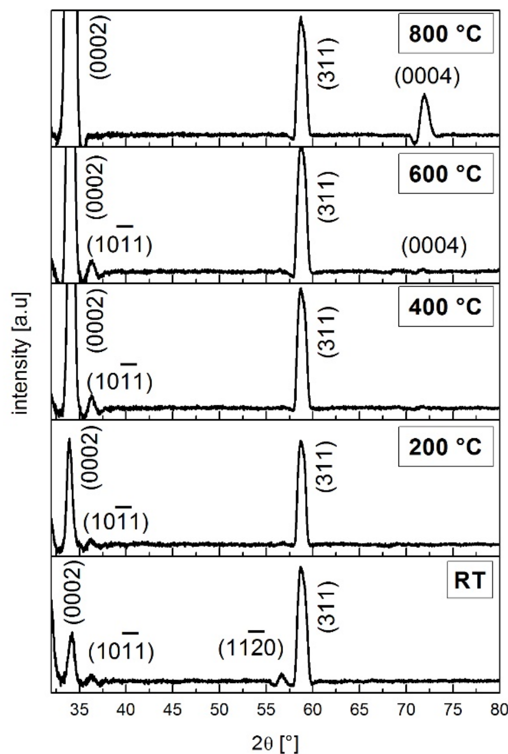

Figure 9: XRD patterns to examine the influence of the substrate temperature on the crystal growth of the GaN films.

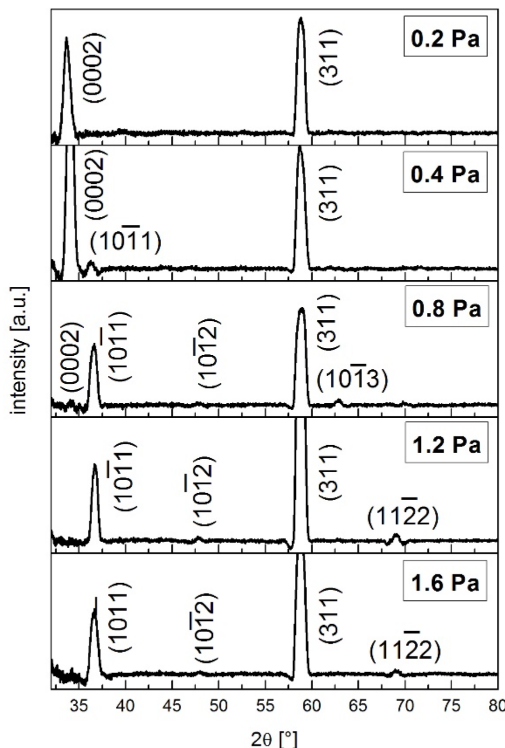

Figure 10: XRD patterns to examine the influence of the nitrogen pressure on the crystal growth.

The surface diffusion length of sputtered adatoms will be increases with inceasing substrate temperature. This leads to highly (0002)-oriented films at 800°C. Corresponding XRD-patterns in Figure 9 shows (0002) and (0004) reflections only. The (0002) orientation is supposed as the plane with the lowest surface energy in hexagonal crystal systems. Due to the Silicon substrate, the (311) orientation at $2\theta = 56{,}2$ ° is visible in the XRD patterns. The influence of the N_2 pressure onto the crystal growth is shown in the XRD pattern of Figure 10. Here it can be seen that the crystallinity increases with decreasing N_2 pressure. Therefore, the film is highly (0002)-oriented at 0,2 Pa. In addition, no peaks for GaAs bonds are detected.

CONCLUSION AND OUTLOOK

High crystallinity can be achieved by applying high substrate temperatures and low N_2 pressures during the synthesis of the GaN films. Furthermore, it is not possible to synthesize GaN films without As content with the abovementioned parameters. As a consequence the influence of the As content on the QE has to be elucidated.

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