Abstract

This thesis describes the development of a fabrication process for broadband Superconductor-Insulator-Superconductor (SIS) tunnel junction devices from $636-802\,GHz$ for the band 2 mixers of the Heterodyne Instrument for the Far Infrared (HIFI) of the Herschel Space Telescope (HSO). The SIS junctions are used as frequency mixers in radioastronomical heterodyne receivers and provide quantum-limited performance at millimeter and submillimeter wavelengths. Further applications of the devices fabricated during the course of this thesis are the SMART multi-pixel, dual frequency ($475\,GHz$ and $800\,GHz$ band) receiver installed at the Kölner Observatorium für Submillimeter Astronomie (KOSMA) at the Gornergrat in Switzerland since 2001 and two instruments at the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) at the Amundson Scott south pole station.

An SIS device consists of a small tunnel junction and an integrated high-frequency tuning circuit in microstrip transmission line technique. To achieve a low-loss transmission through the tuning circuit, both electrodes are possibly made of a superconducting material. The HIFI band 2 crosses the gap frequency of Nb at approximately $700\,GHz$. Above this frequency, the integrated RF tuning circuit made of two Nb electrodes becomes increasingly lossy. On the other hand, the stringent requirements for the band 2 mixers assume an almost flat frequency response of the mixer RF performance. Consequently, a material with a higher gap frequency than Nb has to be used to provide a low-loss microstrip tuning circuit. NbTiN is the material of choice, since its gap frequency is expected to be above $1\,THz$ and its deposition process is compliant to the SIS device fabrication. The SIS devices for HIFI band 2 consists of a Nb-Al/Al_2O_3-Nb tunnel junction which is embedded into a NbTiN-SiO_2-Nb or a NbTiN-SiO_2-Al microstrip tuning circuit.

The influence of fabrication tolerances on the simulated device RF performance, in particular the critical lithography tolerances and the thin film properties are modelled to assess the severe requirements of mixer noise temperature and input bandwidth for band 2 of HIFI. For example, typical NbTiN thin films, fabricated at KOSMA, have a critical temperature of $T_c = 14.5\,K$ and a resistivity of $\rho = 100\,\mu\Omega cm$. The broadband tuning circuits are designed for a fixed NbTiN ground plane quality and allow variations of $\Delta T_c \leq \pm 0.5\,K$ and $\Delta\rho \leq \pm 10\,\mu\Omega cm$. Thus the NbTiN reactive DC magnetron sputtering process has been optimized during this work to yield high quality thin films with a high reproducibility. To this end the influence of many fabrication parameters on the film quality has been investigated. It was found that the substrate temperature during the deposition has a critical impact on the film growth and quality. Since 2002, the KOSMA microfabrication laboratory is equipped with a second sputter system, allowing temperatures up to 800°C by means of an integrated substrate heater. When using the old sputter system, the substrate temperature is influenced indirectly by parameters like the sputter pressure or the magnet configuration. The NbTiN film development results in two independent fabrication processes for both available

sputter systems and qualities of $T_c = 14.5\,K$ and $\rho = 100\,\mu\Omega cm$ for the old system at ambient substrate temperature and $T_c = 15\,K$ and $\rho = 80\,\mu\Omega cm$ for films deposited in the new sputter system at increased substrate temperature.

A second example is the junction area reproducibility. The required accuracy of the junction area, driven by the required precision of the center frequency, is $\Delta A_j/A_{nom} \leq \pm 10\,\%$, where ΔA_j is the standard deviation. In case of a $0.8\,\mu m^2$ junction area, only very small side length variations of approximately $50\,nm$ are allowed. Thus an e-beam lithography (EBL) process for the junction area definition is necessary. In addition, the final junction area is also influenced by the reactive ion etching (RIE) recipe used for the trilayer etch. Recipes with isotropic behavior tend to develop less reproducible junction areas, compared to more anisotropic or directional etch recipes. Gas mixtures of NF_3+CCl_2F_2 and SF_6+CHF_3 result in a directional junction etch with a vertical to lateral aspect ratios of 4:1. The required junction area accuracy can be achieved with these recipes for junction areas of $A_j \approx 1\,\mu m^2$.

The integration of the NbTiN thin film technology into the SIS device fabrication process has been demonstrated by an initial process, using UV lithography for the junction definition and a subsequent self-aligned Nb etching process (SNEP). Later, the fabrication process is converted using a more sophisticated process on the basis of EBL and chemical mechanical polishing (CMP). This process enables a more accurate junction definition and a smaller junction area scattering for junctions down to $0.5\,\mu m^2$.

On the other hand, the devices processed for HIFI band 2 exhibit an subgap current increased by a factor of two e.g. compared to KOSMA $490\,GHz$ devices. This junction leakage results in a reduced RF performance due to the higher shot noise through the barrier. The leakage is attributed to a rough NbTiN surface, which is reproduced in the Nb bottom electrode layer. Then the subsequent Al layer is not completely covering the rough Nb surface and creates, after thermal oxidation, a barrier with increased amount of defects which enable an increased subgap current. Anodic oxidation spectroscopy (AOS) of a junction trilayer has shown broadened "interlayers" at both sides of the barrier layer, indicating a rough NbTiN surface.

The successful integration of the NbTiN thin film technology into the SIS fabrication process and in particular the EBL/CMP process has resulted in the fabrication of devices for HIFI band 2 that are finally incorporated into the flight model (FM) mixers. The measured receiver RF performance of these devices between $636\,GHz$ and $802\,GHz$ is below $200\,K$. At $708\,GHz$, a receiver noise temperature of $81\,K$ is achieved for one of the FM mixers. The integrated receiver noise temperature across the complete frequency band from $636 - 802\,GHz$ is $126\,K$ and $129\,K$ for the two FM mixers and thus meets the integrated HIFI band 2 baseline ($130\,K$). These HIFI band 2 mixers, equipped with devices with a NbTiN based tuning circuit, are the most sensitive mixers developed at KOSMA over the broad frequency range from $636 - 802\,GHz$.