Providing of Ultra-Thin Film Thickness Uniformity by Magnetron Sputtering from Two Sources

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Abstract. To achieve high characteristics of single-photon detectors based on WSi thin films it is necessary to provide high film thickness uniformity more than 95%. This paper presents a mathematical modeling of the thickness uniformity of an ultra-thin film formed by magnetron sputtering from two sources, based on an experimentally determined mass flow from a single magnetron, depending on the location of the magnetrons relative to the substrate holder. According to the results of non-uniformity modeling, the requirements for the design and location of the magnetron unit in the chamber were made, which ensured the required non-uniformity of the film thickness of less than 5%.

1. Introduction
Superconducting single photon nanowire detectors (SNSPD) are designed to detect visible radiation (single photons) (400 ... 780 nm) and near infrared (0.74 ... 2.5 microns). SNSPDs are used as photon counters in various fields: in quantum cryptography, in optical coherent tomography and quantum optical coherent tomography, in LIDAR systems, in astronomical research, and also in testing microcircuits [1]. The application of SNSPD in optical quantum computing is promising, since the implementation of a quantum optical integrated circuit requires a photon source, logic elements, and a photon receiver (detector) [2]. In addition, SNSPDs are in demand in optical systems for long-distance space communications [3].

Single-photon detectors based on superconductors have advantages over alternative ones due to a wider spectral range of detection, high quantum efficiency, high count rate and lower dark count rate, as well as higher operating temperatures [1, 4].

One of the most promising materials for the SNSPD sensitive element is WSi [5], the detectors based on which demonstrate high quantum efficiency up to 93% [6].

The thickness of the superconducting films for SNSPD is less than 10 nm [7]. At these values, a strong change is observed in the superconducting parameters of the material depending on the thickness [8], which leads to a significant effect of the film thickness on the output characteristics of the detector: quantum efficiency, count rate, operating temperature, and the number of dark counts [9, 10, 11]. In this regard, to ensure reproducibility of the output characteristics of the detector, it is necessary to obtain films with a high uniformity of thickness of more than 95%.

One of the most common methods for the formation of superconducting ultrathin films for SNSPDs, which are also used in the laboratory of the Department of Electronic Technologies in Mechanical Engineering, is magnetron sputtering. The formation of the WSi film in our laboratory is carried out at the VUP-11M technological system [12] by sputtering the W and Si targets of two magnetrons. The angle between the axis of each of the magnetrons and the substrate holder is 45°.
center of the substrate holder coincides with the intersection of the magnetron axes [12]. In [13] it was shown that the implementation of the rotation of the substrate holder at a given arrangement of magnetrons will provide the required non-uniformity of the film thickness of less than 5%. However, the current location of the substrate holder in the chamber (in a plane located at an angle to the axis of the vacuum input of the substrate holder) does not allow rotation of the substrate holder, and therefore the formed two-component films have a high non-uniformity of thickness and composition along the substrate.

To ensure film thickness non-uniformity of less than 5%, it is advisable to change the layout and place two magnetrons on one chamber flange symmetrically with respect to the substrate, and the substrate holder on the opposite flange, which will allow rotation of the substrate holder and reduce the non-uniformity of the film thickness and composition.

In this paper, we consider a method for ensuring the required non-uniformity of the thickness of a two-component film of less than 5% by means of the newly developed design of the magnetron assembly. To put forward the requirements for the design of the magnetron assembly (to determine the distance between the magnetron axes and the angle of inclination of the magnetron axis relative to the axis of the substrate holder), a non-uniformity of the film thickness by co-sputtering from two sources is simulated.

2. Experimental determination of the spatial distribution of the W flux from one magnetron

Modeling of thickness non-uniformity depending on the relative position of the magnetrons and the substrate holder is carried out on the basis of a regression model of the spatial distribution of the flux from one magnetron, obtained on the basis of an experimental measurement of the deposition rate.

To determine the material flux from a single magnetron, the mass deposited on quartz resonators fixed at 9 experimental points (Figure 1, a) on a substrate holder is determined using the piezoelectric microweighting method [14]. Tungsten W was deposited at five different distances z between the substrate holder and the magnetron: 50, 70, 90, 110, and 130 mm (Figure 1, b). The formation of a tungsten film by magnetron sputtering is carried out at the VUP-11M setup. The parameters of the deposition mode of the tungsten film [15] are shown in table 1.

![Figure 1](image)

**Figure 1.** The arrangement of the experimental points: (a) the location of the substrate holder relative to the magnetron; (b) the location of the quartz resonators on the substrate holder.

| Parameter | Value |
|-----------|-------|
| Signal   | Pulse |
| Power (W) | 120   |

**Table 1.** The parameters of the W films magnetron sputtering.
As a result of the experiments, the specific mass of the film deposited at each of the experimental points was calculated. The flux $Q \ [g/(cm^2 \cdot s)]$ is determined from the ratio of the specific gravity to the film deposition time $t$, the calculated flux values at the experimental points for the distances $z$ from the magnetron are presented in Table 2.

| Resonator No | $z_1 = 50 \text{ mm}$ | $z_2 = 70 \text{ mm}$ | $z_3 = 90 \text{ mm}$ | $z_4 = 110 \text{ mm}$ | $z_5 = 130 \text{ mm}$ |
|--------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 1            | 0.491                  | 0.339                  | 0.337                  | 0.274                  | 0.187                  |
| 2            | 0.984                  | 0.447                  | 0.478                  | 0.309                  | 0.245                  |
| 3            | 0.536                  | 0.354                  | 0.444                  | 0.252                  | 0.240                  |
| 4            | 0.884                  | 0.618                  | 0.492                  | 0.415                  | 0.279                  |
| 5            | 2.086                  | 0.958                  | 0.763                  | 0.450                  | 0.339                  |
| 6            | 0.808                  | 0.607                  | 0.534                  | 0.286                  | 0.289                  |
| 7            | 0.537                  | 0.501                  | 0.417                  | 0.321                  | 0.248                  |
| 8            | 0.799                  | 0.603                  | 0.570                  | 0.322                  | 0.285                  |
| 9            | 0.510                  | 0.395                  | 0.386                  | 0.219                  | 0.236                  |

A mathematical model of the dependence of the material flow on spatial coordinates relative to the magnetron was obtained on the basis of the experimental values of the flux $Q$ using regression analysis in a Mathcad environment.

Using the third-order polynomial regression function, we obtained the regression models of the flow $Q$ depending on the location of the point on the substrate holder in the Cartesian coordinates $x, y$. The coordinates of the extrema of the functions were found to eliminate the influence of the error of fixing the central resonator on the substrate holder (mismatch between the center of the resonator 5 and the axis of the magnetron (figure 1 a, b). Then the coordinates of the experimental points 1 ... 9 for each fixing height of the substrate holder $z$ are translated into polar coordinates $r$ and $\phi$, and flux values $Q$ are averaged over the angle $\phi$ according to the mean value theorem. Thus, we obtain the functions of the flux $Q(r)$ depending on the radius relative to the magnetron axis for each height.

The obtained $Q(r)$ curves at heights $z_1$ - $z_5$ are combined by the regression function into a model of the spatial distribution of the material flow $Q$ at a given point from one magnetron depending on the radius $r$ and height $z$ (figure 2), where $r$ and $z$ are the radius and height in cylindrical coordinates relative to the magnetron. The location of the magnetron corresponds to the origin on the graphs.

The obtained spatial distribution of the material flow from one magnetron $Q$ allows us to simulate the dependence of the non-uniformity of the film thickness on the relative position of the substrate and magnetrons during sputtering from two sources.
Figure 2. Regression model of the dependence of the flux \( Q \, [\text{g/(cm}^2\cdot\text{s})] \) on the radius \( r \) and height \( z \) (the location of the magnetron corresponds to the origin): a) contour plot; b) surface graph.

3. Modeling film thickness non-uniformity depending on the magnetron location relative to the substrate

To simulate the film thickness non-uniformity depending on the substrate location relative to the magnetron, the coordinates \( r \) and \( z \) are expressed in terms of angle \( \beta \) and distances \( B \) and \( L \) (figure 3).

Figure 3. The calculational scheme of the substrate layout relative to the magnetrons.

Based on the flow distribution, a film thickness non-uniformity model \( \Delta \) and a specific film deposition rate (which is equivalent to \( Q \) flow) at sputtering from two sources were built in Mathcad depending on \( L \) and \( B \) at an angle \( \beta \) from 0 to 45° in increments of 5° with ranges of variation of \( L \) from 0 to 40 mm, and of \( B \) from 90 to 130 mm. From 10 obtained plots of the non-uniformity surface \( \Delta \) depending on the distances \( L \) and \( B \), it was found that the smallest angle \( \beta \), at which \( \Delta \) is less than 5%, is equal to 5°. With an increase in \( \beta \), the ranges \( B \) and \( L \), in which the condition \( \Delta < 5\% \) is fulfilled, increase, and these regions shift towards lower values of \( B \). Based on the plots of the deposition rate versus \( B \) and \( L \) for various \( \beta \), it was found that the effect of angle \( \beta \) on the deposition rate is negligible. The deposition rate decreases with increasing distance \( B \) and eccentricity \( L \).

In addition to the film thickness non-uniformity \( \Delta < 5\% \), the arrangement of magnetrons in the chamber should provide a high film deposition rate. The angle of magnetron inclination \( \beta \) should be
the smallest in order to place the magnetron assembly in the chamber of the VUP-11M system. Based on these requirements and the simulation of non-uniformity and deposition rate, the angle $\beta = 10^\circ$ was chosen. At $\beta = 10^\circ$, non-uniformity of less than 5% is ensured with a distance $B = 105...120$ mm and an eccentricity $L = 0...5$ mm. In the selected range, the highest deposition rate of 0.496 g/(cm2-s) is achieved at $L = 0$ mm and $B = 105$ mm. Models of non-uniformity of the film thickness $\Delta$ [%] and deposition rate $Q$ [g/(cm2-s)] at $\beta = 10^\circ$ depending on $L$ and $B$ are presented in figures 4 and 5, respectively.

![Figure 4](image1.png)

**Figure 4.** Model of the film thickness non-uniformity $\Delta$ [%] depending on the distance $B$ from the substrate holder and eccentricity $L$ at magnetron inclination angle $\beta = 10^\circ$: a) surface graph; b) contour plot.

![Figure 5](image2.png)

**Figure 5.** Model of the film deposition rate $Q$ [g/(cm2-s)] depending on the distance $B$ from the substrate holder and eccentricity $L$ at magnetron inclination angle $\beta = 10^\circ$: a) surface graph; b) contour plot.

Based on the modeling of the thickness and deposition rate of the film at Mathcad, the following requirements for the location of the magnetrons relative to the substrate holder, which provide the film thickness non-uniformity is less than 5%, have been put forward:
- magnetron inclination angle $\beta > 10^\circ$
- eccentricity $L < 5$ mm
- distance $B = 105 \ldots 130$ mm

According to the results of modeling the film deposition rate for $\beta = 10^\circ$ in the indicated ranges of $L$ and $B$, the maximum deposition of $0.496$ g/(cm$^2$·s) is provided at $L = 0$ mm and $B = 105$ mm. Based on the above requirements, $k$ and $h$ are chosen (figure 6):

$$h = B \cos \beta \cdot L \sin \beta = 105 \cdot \cos(10^\circ) = 103.4 \approx 104$ mm \quad (1)$$

$$k = B \sin \beta + L \cos \beta = 105 \cdot \sin(10^\circ) = 18.2 \approx 20$ mm \quad (2)$$

**Figure 6.** The calculational scheme of the magnetron location relative to the substrate.

Thus, based on the requirements for thickness non-uniformity of less than 5%, a high film deposition rate and a small angle of inclination, the distances from the substrate holder to the magnetron are chosen to be $k = 20$ mm and $h = 104$ mm at an angle $\beta = 10^\circ$, which satisfies the required conditions for ensuring thickness non-uniformity films less than 5%. This arrangement of the magnetron assembly can be implemented at the VUP-11M installation for the formation of two-component WSi thin films for single-photon detectors.

4. Conclusions
Based on the simulation of the WSi film thickness non-uniformity depending on the location of the magnetrons relative to the substrate holder, it was determined that the required non-uniformity of the thickness of less than 5% of the film is ensured at $\beta = 10^\circ$, distance $B = 105 \ldots 120$ mm and eccentricity $L = 0 \ldots 5$ mm. In the selected range, the highest deposition rate of $0.496$ g/(cm$^2$·s) is achieved at $L = 0$ mm and $B = 105$ mm, which corresponds to the distance between magnetrons $2k = 40$ mm, the distance between magnetrons and substrate holder $h = 104$ mm at an angle between the magnetron axes and substrate holder $\beta = 10^\circ$. This arrangement of the magnetron assembly can subsequently be implemented on the VUP-11M system for the formation of two-component WSi thin films for single-photon detectors.

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