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RESEARCH ARTICLE

Comparison of magnetron sputtering systems for high-rate deposition of thick copper layers for microelectronic applications

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Abstract

Objectives. When designing production equipment for the implementation of metal film deposition processes, the selection of technological sources for providing the required quality (structure, appearance), maximum process efficiency, and productivity, poses a challenging task. Since laboratory results often differ from issues faced in production processes, this choice becomes even more difficult under real production conditions due to a lack of sources for comparison. The purpose of the present work is therefore to compare magnetron deposition methods under real industrial conditions (planar extended magnetron, liquid-phase magnetron and cylindrical magnetron with a rotating cathode), identify their advantages and disadvantages along with features of thus-formed metal films, analyze the economic feasibility of each variant, and give practical recommendations for selecting a source when implementing the described process.

Methods. Films were deposited using magnetron sputtering system. Roughness was measured using a MarSurf PS1 profilometer. The structure of the films was studied using a Hitachi SU1510 scanning electron microscope. Film thicknesses were measured by X-ray fluorescence analysis using a Fisherscope X-RAY XDV-SDD measuring instrument.

Results. Sources of magnetron sputtering for the high-rate deposition of metallization layers under industrial conditions are considered. Obtained samples were compared according to the following criteria: deposition rate while maintaining the required quality, surface defects, film grain size, roughness, uniformity of the deposited layer, deposition efficiency (the ratio of the metal deposited directly onto the substrate to the amount of metal produced during the process). A comparison of the characteristics showed that the deposition rate for the liquid-phase magnetron is commensurate with the similar parameter for the cylindrical magnetron, exceeding the rate for the classical planar magnetron by about 4 times while maintaining the uniform appearance of the samples. The samples deposited with a liquid-phase magnetron had the highest roughness and the largest grain size. Although the cheapest method, liquid-phase magnetron sputtering achieved the lowest sputtering efficiency.

Conclusions. The choice of the deposition method depends on the problem to be solved. The rotatable magnetron system can be considered optimal in terms of cost, deposition rate, and quality of the deposited layers. Liquid-phase magnetron sputtering is recommended for low-cost high-speed deposition where there are no strict requirements for appearance, or in case of operation of small-sized equipment.

Keywords: magnetron, liquid phase magnetron, planar magnetron, rotatable magnetron, metal film deposition, deposition efficiency, productive methods, deposition rate, choice of deposition method

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НАУЧНАЯ СТАТЬЯ

Анализ источников магнетронного распыления для осаждения толстых слоев меди с высокой скоростью для изделий микроэлектроники

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Резюме

Цели. При проектировании производственного оборудования для реализации процессов осаждения металлических пленок актуальной задачей является выбор технологических источников, которые должны обеспечивать требуемое качество (структуру, внешний вид), максимальные эффективность процесса и производительность. Однако в реальных производственных условиях сделать этот выбор сложно в связи с недостаточностью сравнительных материалов источников. Лабораторные результаты нередко отличаются от результатов на производстве. Цель работы – сравнить методы магнетронного осаждения в реальных промышленных условиях (планарном протяженном магнетроне, жидкофазном магнетроне и цилиндрическом магнетроне с вращающимся катодом), выявить их преимущества, недостатки и особенности формирования металлических пленок, проанализировать экономическую целесообразность выбора каждого из них и дать практические рекомендации выбора источника при реализации требуемого процесса.

Методы. Для осаждения пленок применены методы ионного распыления в магнетронных системах. Измерение шероховатости проводилось с помощью профилометра MarSurf PS1. Структура пленок изучалась с помощью растрового электронного микроскопа Hitachi SU1510. Толщины пленок измерялись методом рентгено-флуорисцентного анализа с помощью прибора Fisherscope X-RAY XDV-SDD.

Результаты. Рассмотрены источники магнетронного распыления для скоростного осаждения слоев металлизации в промышленных условиях. Проведено сравнение полученных образцов по критериям: скорость осаждения с сохранением требуемого качества, поверхностные дефекты, размер зерна пленки, шероховатость, равномерность осажденного слоя, эффективность осаждения (отношение металла, осажденного непосредственно на подложку, к количеству выработанного металла во время процесса). Сравнение характеристик показало, что скорость осаждения для жидкофазного магнетрона соизмерима с аналогичным параметром для цилиндрического магнетрона и превосходит примерно в 4 раза скорость для классического планарного магнетрона при сохранении единого внешнего вида образцов. Самой высокой шероховатостью и самым крупным размером зерна обладают образцы, осажденные жидкофазным магнетроном. Самой низкой эффективностью распыления обладает метод жидкофазного магнетронного распыления, который является самым дешевым.

Выводы. Выбор метода осаждения зависит от решаемой задачи. Оптимальным по стоимости, скорости осаждения и качеству осаждаемых слоев можно считать магнетрон с цилиндрическим вращающимся катодом. Жидкофазное магнетронное распыление рекомендовано использовать для дешевого скоростного осаждения, при котором нет жестких требований к внешнему виду, или в случае эксплуатации малогабаритного оборудования.

Ключевые слова: магнетрон, жидкофазный магнетрон, планарный магнетрон, цилиндрический магнетрон, осаждение металлических пленок, эффективность осаждения, производительные методы, скорость осаждения, выбор метода осаждения

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INTRODUCTION

In the rapidly developing field of microelectronics, there are constantly increasing requirements for devices whose integral part comprises boards on a ceramic base having a conductive copper layer. Copper conductive layers on ceramic substrates are used in devices such as switching boards, thermoelectric modules, power diodes, power transistors, and integrated circuits [1–6]. In terms of their dimensions, appearance, productivity, and cost, the increasing requirements for the quality and reliability of products in turn affects the materials and technological processes used in the manufacture of individual product elements. This leads among other things to the need to find more productive methods for the deposition of metallization coatings (copper, aluminum, titanium, etc.) as compared with traditional approaches.

However, the choice of the optimal method is difficult due to a lack of literature data providing such comparison criteria as surface roughness, grain size, surface structure, deposition rate, and cost of the deposited layer.

The purpose of the present work is therefore to analyze the methods of deposition of conductive layers according to the above indicated criteria on the example of copper layers.

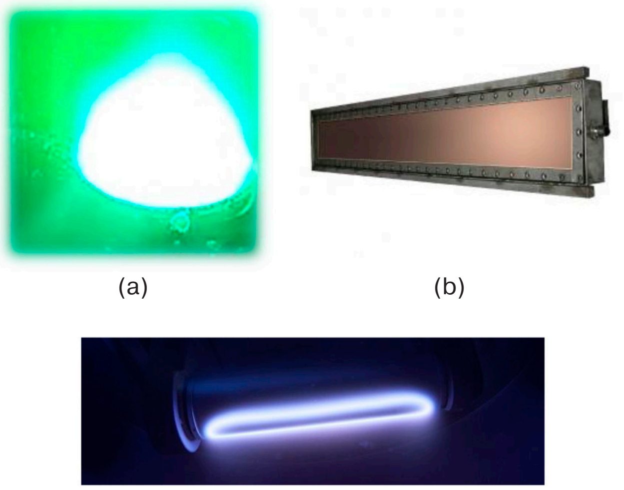
DEPOSITION RATE

To date, the magnetron sputtering methods combining the highest deposition rates with a satisfactory quality of deposited coatings include:

- ion sputtering in magnetron systems with a liquid target (liquid-phase magnetron sputtering, LPMS) [6–9] (Fig. 1a);
- with an extended planar target [10] (Fig. 1b);
- with a cylindrical rotating target [11, 12] (Fig. 1c).

A high-quality coating is understood as one that minimizes the number of surface defects (droplet phase, various inclusions, craters) and internal defects (pores), but at the same time provides sufficient adhesion to ensure the performance of the product.

As a comparison, Table 1 shows the values of the deposition rate by the methods described. Presented data are obtained experimentally. The distance from the magnetron surface to the substrates is 100 mm. Aluminum nitride (AlN) with roughness *Ra* = 10 nm was used as substrates.



(a) (b) (c)

Fig. 1. View of magnetrons for technological applications: (a) liquid-phase magnetron, (b) planar magnetron, (c) cylindrical magnetron with a rotating cathode [7]

As compared with a cylindrical magnetron with a rotating target, it is impossible to achieve the same specific power at the cathode of an extended planar magnetron while maintaining the required quality of

Table 1. Comparison of the maximum deposition rates achieved on a fixed substrate

Magnetron sputtering system	With liquid target (crucible ∅86 mm)	With extended planar target (108 × 440 mm)	With cylindrical rotating target (450 × ∅152 mm)
Deposition rate	40 μm/min	10 μm/min	41 μm/min

Table 2. Comparison of surface roughness

Sample number	Magnetron sputtering system		
	With liquid target (crucible ∅86 mm)	With extended planar target (108 × 440 mm)	With cylindrical rotating target (450 × ∅152 mm)
1	68	31	51
2	70	28	44
3	98	26	51
4	89	29	42
Average value	81	28	42

Table 3. Grain size of copper surface

Grain size, μm	Magnetron sputtering system		
	With liquid target (crucible ∅86 mm)	With planar target (108 × 440 mm)	With cylindrical rotating target (450 × ∅152 mm)
Minimum	3	3	3
Maximum	20	6	11

the deposited films due to its overheating. This explains such a difference in the deposition rates.

As can be seen from Table 1, the deposition methods with a liquid and with a cylindrical rotating target have comparable results. However, a standard magnetron with an extended planar target does not provide such high deposition rates.

SURFACE ROUGHNESS

The values of the copper surface roughness (*Ra*, nm), which was measured using a MarSurf PS1 profilometer (Mahr GMBH, Germany), are presented in Table 2.

As can be seen, the classical magnetron with an extended planar target has the lowest roughness, which is explained by the low deposition rate. The method with a rotating cylindrical target has a roughness 1.5 times higher. The method with a liquid target has a roughness almost 4 times higher, which can become critical for some production tasks [13–15][1].

STRUCTURE OF THE FILMS

Figure 2 shows the surface structure and grain size. Studies were carried out on a Hitachi SU1510 scanning electron microscope (HITACHI, Japan). The grain size is indicated in Table 3.

Classical sputtering with a planar extended target provides the finest grain. For the magnetron with a cylindrical rotating target the grain size only 2 times larger. The method with a liquid target provides the largest grain, which is associated with a high thermal effect on the substrate caused by this type of a magnetron. By reducing the deposition rate on a fixed substrate to 20 μm/min, a grain size of up to 4 μm is achieved on a magnetron with a rotating cylindrical cathode, which is comparable to the grain size achieved on a planar magnetron with an extended target. However, the deposition rate is higher for a cylindrical magnetron.

THICKNESS UNIFORMITY OF DEPOSITED LAYER

The copper coating thickness was measured using a Fisherscope X-RAY XDV-SDD X-ray fluorescence thickness gauge (Fischer GMBH, Germany)[2]. Scanning was carried out in the center and along the perimeter of the substrate with an indent of 3 mm from the edge. An evaluation of the non-uniformity showed that sputtering methods having a liquid target and those

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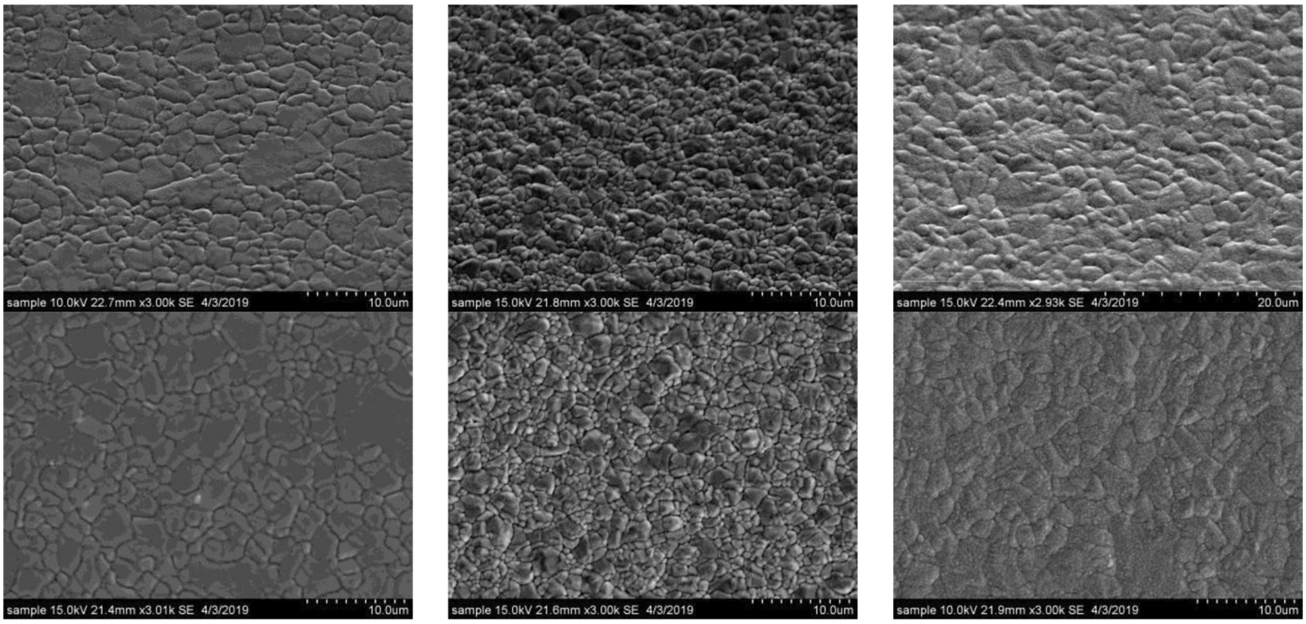

(a) (b) (c)

Fig. 2. View of the surface deposited using: (a) the LPMS method, (b) a planar magnetron with an extended target, (c) a magnetron with a cylindrical rotating target

Table 4. Evaluation of material efficiency

Parameter	Magnetron sputtering system		
	With liquid target (crucible ∅86 mm)	With planar target (108 × 440 mm)	With cylindrical rotating target (450 × ∅152 mm)
Fraction of material deposited on substrates, %	~20	~60	~90
Production of target material, %	~90–100	~45	~70
Efficiency, %	20	27	63

Table 5. Estimation of deposition cost of a 50 µm thick layer

Parameter	Magnetron sputtering system		
	With liquid target (crucible ∅86 mm)	With extended planar target (108 × 440 mm)	With cylindrical rotating target (450 × ∅152 mm)
Maximum loading of substrates in one process with dimensions of 60 × 48 mm	20	70	80
Number of processes on one target, pcs.	150 g (loading in the form of granules for 1 process)	5	40
Approximate cost per target, a.u.	1 kg – *X*	1 pc. – 4.5*X*	1 pc. – 29*X*
Cost of deposited layer per substrate, a.u.	~*X*/131	~*X*/80	~*X*/111

with a classical extended planar magnetron provide a layer non-uniformity of no more than ±5%, while for a magnetron with a cylindrical rotating target, the layer non-uniformity does not exceed ±3%.

SPUTTERING EFFICIENCY

The material utilization factor was estimated as follows: the fraction of the material removed from the target during its life cycle was multiplied by the fraction of the material that was deposited on the substrates. To convert to a percentage, the coefficient is multiplied by 100%. The calculation results are given in Table 4.

Calculations have shown that the most efficient sputtering is provided by a magnetron with a liquid target.

The cost of the deposited layer 50 µm thick was estimated taking into account the cost of the material and the efficiency of the deposited layer (Table 5).

The average price on the market of granulated vacuum-melted copper, *X* was taken as the base. The costs of a planar and a cylindrical rotating target are given in coefficients relative to the base cost of *X* arbitrary units (a.u.).

Despite the low efficiency of deposition, the magnetron with a liquid target is the most cost-effective due to the absence of the need to manufacture a target of complex shape. Regardless of the high cost of the target due to its increased efficiency, the magnetron with a rotating cylindrical target is close to the magnetron with a liquid target in terms of the cost of the "deposited layer."

CONCLUSIONS

The present work analyzed copper films obtained by magnetron sputtering using a cylindrical magnetron, a planar magnetron, and a liquid-phase magnetron. The comparison of deposition methods according to the criteria of "coating deposition rate," "coating structure and surface defects," "roughness," "uniformity of the deposited layer," "sputtering efficiency" and "economic feasibility" confirmed that there is no single universal method that offers optimal performance in terms of all these parameters. For example, the optimal cost of deposition is provided by the method of liquid-phase magnetron sputtering, where the relative cost of the deposited layer is *X*/131 a.u. This compares to *X*/111 a.u. in the case of cylindrical magnetron sputtering and *X*/80 a.u. in the case of a planar extended magnetron. At the same time, the LPMS method loses out to cylindrical magnetron sputtering in terms of surface structure criteria (roughness, grain size, and surface defects). The deposition rates of about 40 µm/min are comparable under the described conditions.

When choosing a coating deposition method, it is necessary to clearly understand the problem to be solved, namely, the requirements for productivity, coating quality (structure and defects), and cost. The magnetron with a cylindrical rotating cathode can be considered as optimal in terms of the cost of the deposited layer, the rate of deposition, and the quality of the deposited layers. However, due to the large dimensions of such sources, it cannot be used for small-sized vacuum chambers. It is recommended to use LPMS for inexpensive high-speed deposition, including operation in vacuum chambers with small dimensions. Although seemingly optimal, the deposition method using extended planar magnetron systems is outperformed by LPMS and cylindrical magnetrons.

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