A pulser for medium-frequency modulated direct-current reactive sputter deposition of insulators

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We present the circuit design of a unit for medium-frequency modulated direct-current (dc) reactive sputter deposition of electrical insulators. The unit is connected in series between a commercial dc sputtering power supply and a sputtering cathode (target). It modulates the voltage applied to the sputtering cathode in a pulsed, asymmetric bipolar fashion. The pulsing effectively eliminates the problem of arcing at the target surface. The simple circuit is a low-cost, flexible alternative to commercially available units. To demonstrate its utility, we deposited a film of 5 SiO₂/TiO₂ bilayers, forming a highly reflective dielectric optical mirror with a stop band centered near a wavelength in air of 600 nm. © 2000 American Institute of Physics. [S0034-6748(00)03506-1]

I. BACKGROUND

Traditionally, researchers have used radio-frequency (rf) sputtering to deposit electrically insulating films.¹ With this technique, the sputtering cathode (target) can be either metallic or ceramic. For example, to obtain insulating metal–oxide or metal–nitride films with a metal target, typically the gas mixture in the vacuum chamber contains a working gas (e.g., Ar) and a reactive gas, O_2 or N_2 , respectively. When a ceramic target is used, a reactive gas can be added to control the stoichiometry of the deposited film.

Although rf sputtering is a well-known and demonstrably powerful laboratory technique for depositing insulating films, it requires a significant investment in instrumentation, including a rf power supply and a high-power impedance matching network. Furthermore, in practice, the experimentalist must use proper rf shielding and grounding to avoid electromagnetic interference with other laboratory equipment. Additionally, impedance matching between the power supply and plasma may be difficult to obtain and will depend on the target material, gas pressure and mixture, and the internal chamber configuration.

Medium-frequency sputtering is a viable alternative to rf sputtering for research and production applications. Este and Westwood reported one of the first investigations of this technique.² Subsequently, there have been vigorous efforts to exploit the advantages of such quasi-direct-current sputtering techniques. For example, researchers have used pulsed direct-current (dc) power for the reactive deposition of dielectrics from metallic targets.^{3–5} In this article, we discuss the problem of arcing at the target surface inherent to high-deposition-rate reactive sputtering of electrical insulators. Typically, this unwanted effect yields films of poor quality and in the worse case, arcing prohibits dc sputtering altogether.

As a solution to this problem, we present a complete circuit design of a pulsing unit that we have inserted between a commercial dc sputtering power supply and a metallic sputtering cathode. It is similar to commercially available units.⁶ Our primary goal of this article is to offer researchers a relatively low-cost, flexible alternative to the units now on the market. Furthermore, it is our hope that this article will stimulate further work in this area.

As a demonstration of our unit, we deposited a film of five SiO_2/TiO_2 bilayers, forming a highly reflective dielectric optical mirror with a stop band centered near a wavelength in air of 600 nm. We will discuss the utility of the pulser in depositing this structure and will present optical transmission data for the stack.

II. CIRCUIT OPERATION

When the sputtering gas mix includes a species that reacts with the target material in a plasma environment, the reactant enters the gas phase. Some of the material is scattered and deposits on the target surface outside of the socalled "race track" area (where the sputtering rate is enhanced due to the confinement of the plasma by the sputtering gun magnets). When the reactant is electrically insulating, a parasitic capacitance is formed between the conducting target and the plasma. For a small area A and thickness d of this insulating film on the target surface, the capacitance is

$$C = \epsilon_f \epsilon_0 A/d, \tag{1}$$

where ϵ_f is the dielectric constant of the film and ϵ_0 is the permittivity of free space. For a current density *J*, the charge on the capacitor in a time *t* will be approximately

$$Q = JAt = CV, \tag{2}$$

where V is the voltage across the capacitor. The electric field in the film is given by

$$E = V/d = Jt/(\epsilon_f \epsilon_0). \tag{3}$$

We can now solve for the time it will take for the dielectric in the effective capacitor to breakdown,

2560

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FIG. 1. Schematic of the pulser circuit.

$$t_b = \epsilon_0 \epsilon_f E_b / J, \tag{4}$$

where the subscript, *b*, indicates breakdown values. Equation (4) suggests that a solution to the problem of arcing is to discharge the parasitic capacitor periodically, at a frequency higher than $1/t_b$. Belkind *et al.* present a recent, detailed study of this problem; we refer the reader to their work.⁷

We distinguish two classes of arcs: violent arcs and microarcs. To the sputtering system operator, violent arcs are obvious: effectively, the sputtering cathode is shorted to ground and the plasma flickers. Occasionally, sparks are ejected from the cathode (presumably hot particles of the target material). If this violent arcing is frequent enough, reactive sputtering cannot be carried out. The second, less obvious type of arc can be observed on an oscilloscope monitoring the cathode voltage, but may be missed if the operator only monitors the plasma visually and with the typical accompanying power supply. Such microarcs appear as short-lived (tens of microseconds) disturbances in the cathode voltage.

We have correlated the presence of these microarcs with diminished film quality. When depositing a silicon dioxide film by reactive sputtering, we noted such arcs on an oscilloscope. Subsequently, under an optical microscope, we observed particles embedded in the film.

It is our experience that both violent arcs and microarcs are eliminated when the pulser circuit (shown schematically in Fig. 1) is used. Power from a dc sputtering power supply (Advanced Energy, Model MDX-1K) is fed into an in-house wound ferrite-core inductor. This inductor is placed in series with the sputter cathode. The inductor is tapped, forming an autotransformer. Between the tap and ground we connected a fast semiconductor switch. When the switch is open, dc current passes through the inductor directly to the cathode. When the switch is closed [by a drop in the input complementary metal–oxide–semiconductor (CMOS) level], the inductor functions as an autotransformer: the voltage applied



FIG. 2. Oscilloscope traces of the sputtering cathode voltage (top) and the pulser trigger (bottom). Here (a) and (b) correspond to the Si and Ti sputtering targets, respectively. The dc levels of these targets are given in Table I. The dotted line indicates the ground level common to the sputtering power supply and the chamber. The trigger pulse width is approximately 3 μ s and the pulse repetition rate was 60 kHz.

to the cathode is reversed in polarity, to a voltage level proportional to the transformer turns ratio, ~ 1.8 . After a suitable time (3–5 μ s), the switch is opened and dc power is again applied to the cathode (with an initial voltage overshoot). This triggering of the pulser circuit is repeated periodically; we conveniently use a commercial signal generator with adjustable frequency and duty cycle.

Figure 2 shows the oscilloscope traces of the cathode voltage (top) and pulser trigger (bottom) for two different sputtering targets, Ti and Si. The sputtering conditions are presented in Table I and our deposition system is described elsewhere.⁸ Both targets were sputtered in the same ambient gas mixture, 5 mT Ar/0.5 mT O₂, and the sputtering power supply was operated in a constant power mode.

As is evident, the negative voltage overshoot is highest for the Ti target, which we attribute to the greater stored energy in the inductor due to the higher current level relative to that used for the Si target.

III. RESULTS

Figure 3 shows the optical transmission spectrum for a film consisting of five bilayers of SiO_2/TiO_2 on a borosilicate glass substrate. We acquired these data with a commer-

TABLE I. Deposition conditions, including the sputtering target materials and their purity, the power output by the sputtering power supply, the dc voltage level of the sputtering cathode, and the film deposition rate on the substrate of the corresponding oxide (estimated from optical data). The substrate temperature was approximately constant for the duration of the film deposition.

Material, Purity	Power (W)	Voltage (V dc)	Deposition rate (A/s)
Si, 5N	90	329	1.8
Ti, 3N5	225	364	0.8
Substrate temperature		~300 °C	
Target-substrate distance		7 cm	



FIG. 3. Optical transmission versus wavelength for a film of five SiO_2/TiO_2 bilayers on a borosilicate glass substrate.

cial UV-visible spectrophotometer (Cary 1E). The data show a strong optical stopband centered near 600 nm; approximately 97% of the incident optical power was rejected. Clear transmission resonances are present on both sides of the stopband, indicating that the optical loss in the stack is minimal.

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