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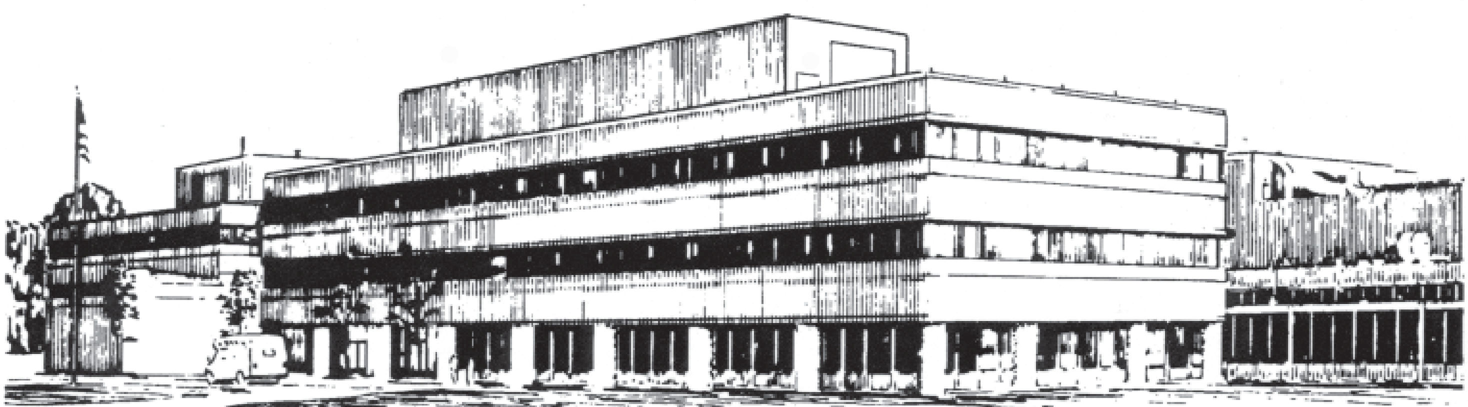

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Development of a silicon based electron beam transmission window for use in a KrF excimer laser system

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ABSTRACT

Princeton Plasma Physics Laboratory (PPPL), in collaboration with Naval Research Laboratory (NRL), is currently investigating various novel materials (single crystal silicon, <100>, <110> and <111>) for use as electron beam transmission windows in a KrF excimer laser system. The primary function of the window is to isolate the active medium (excimer gas) from the excitation mechanism (field-emission diodes). Chosen window geometry must accommodate electron energy transfer greater than 80% (750 keV), while maintaining structural integrity during mechanical load (1.3 - 2.0 atm base pressure differential, approximate 0.5 atm cyclic pressure amplitude, 5 Hz repetition rate) and thermal load across the entire hibachi area (approximate 0.9 $W \cdot cm^{-2}$). In addition, the window must be chemically resistant to attack by fluorine free-radicals (hydrofluoric acid, secondary). In accordance with these structural, functional, and operational parameters, a 22.4 mm square silicon prototype window, coated with 500 nm thin-

film silicon nitride (Si_3N_4), has been fabricated. The window consists of 81 square panes with a thickness of 0.019 mm ± 0.001 mm. Stiffened (orthogonal) sections are 0.065 mm in width and 0.500 mm thick (approximate). Appended drawing (FIG. 1) depicts the window configuration. Assessment of silicon (and silicon nitride) material properties and CAD modeling/analysis of the window design suggest that silicon may be a viable solution to inherent parameters and constraints.

I. INTRODUCTION

The barrier (electron beam transmission window) that separates the excimer gas from dual coaxial double-pass field-emission diodes is an integral component of krypton fluoride (KrF) excimer lasers (for use as Inertial Confinement Fusion (ICF) reactor drivers) [1]. Separation of the active medium from the excitation mechanism involves consideration of extraneous parameters (i.e. differential pressure, thermal accumulation, transmission impedance, etc.) [1]. Composition of the excimer gas (approximate 0.5% diatomic fluorine, molar basis) limits materials selection to relatively inert (chemical) species [2]. It has been proposed to employ novel materials and processing techniques developed for micro-electro-mechanical systems (MEMS) technology, to address these issues [1].

Semiconductor (Si) wafers processed with microlithographic techniques developed for the MEMS industry exhibit low torsional/bending and thermal stress under applied loading [3]. This technology has been demonstrated through the manufacture of microstructured thin diaphragms as device components (i.e. microcalorimetry, nuclide detection, etc.) [4]. Microlithography, via controlled anisotropic etch, facilitates addition of an orthogonal stiffener array without significant membrane area reduction [5].

Thin-film deposition of a chemical-resistant substrate will inhibit direct fluorination of the silicon surface [6].

II. COMPUTER ASSISTED ANALYSIS

Three-dimensional structural analysis was performed via ANSYS simulation software and relevant sourcecodes to determine dynamic stress concentrations (shear, tension, and compression) experienced as a function of thermal and mechanical load variations [7]. The objective was to obtain feasible output data for material properties (i.e. deflection, stress, vibration, buckling, etc.), as a function of specified (variable) source code input [7]. Chosen model for window design is as follows: square-planar geometry reinforced with orthogonal stiffeners and perimeter frame (for structural support and thermal contact with mount apparatus) [8]. Orthogonal configuration provides sufficient resistance to out-of-plane loading (mechanical) while maintaining relatively uniform (biaxial) distribution of in-plane stresses as bulk temperature increases [8]. Dihedral symmetry (90º rotation about normal axis) of window design permits finite element analysis (FEA) via consideration of a representative quadrant [9]. Candidate materials were selected, as per the following characteristics: low material density, high thermal conductivity, low thermal expansion coefficient, low Young's modulus, low Poisson's ratio, high tensile strength, low ductile-to-brittle transition temperature, high chemical (fluorine) resistance, and high resistance to electron-induced radiation damage [10].

Electron transmission analysis was performed via the MCNP general-purpose Monte Carlo N-Particle code for electron transport, including the capability to calculate eigenvalues for critical systems [11]. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first and second degree elliptical tori [11]. Pointwise cross-section data are used. A continuous-slowing-down model is used for electron transport that accounts for x-rays, scattering phenomenon (i.e. backscatter) and bremsstrahlung [11]. The National Institute of Standards and Technology (NIST) ESTAR Stopping Power and Range Tables for Electrons (FORTRAN-77 source code) were referenced as output verification for Monte Carlo simulation [12]. ESTAR output data is a function of incident electron energy (MeV) and mass attenuation coefficient ($cm^2 \cdot g^{-1}$) of absorbing material(s) [12]. Linear attenuation coefficient (i.e. product of mass attenuation coefficient and absorbing material density) is applied to determine linear stopping power (electron energy deposition per linear path length, $MeV \cdot cm^{-1}$) [12]. NIST ESTAR does not account for multiple/random scattering and was therefore not implemented as the primary means for analysis (inaccurate at low energies) [12].

Chemical inertia of materials, in the presence of fluorine gas and hydrofluoric acid, was determined via National Oceanic and Atmospheric Administration (NOAA) Computer-Aided Management of Emergency Operations (CAMEO), Chemical Reactivity Worksheet (version 1.5) [13]. This application determines the potential reactivity of substances and/or mixtures of substances [13]. The data files (ASCII delimited file format) were modified to include substances not listed in the CAMEO chemical database [13]. Each substance was assigned to one or more reactive groups, based on the known chemistry of that substance [13]. To predict the reactivity of a mixture of chemicals, the worksheet first identifies the reactive groups to which the chemicals belong, and then predicts chemical reactions likely to occur when members of these groups are mixed together [13].

III. THEORETICAL ANALYSIS

Ability of material to sustain cyclic dynamic stress without damage to cell structure is determined by examining stress-strain behavior for specified geometry and composition [14]. Silicon has high failure resistance in comparison to other candidate materials, as per loading parameters of KrF excimer laser system [15]. The relatively high Young's modulus of single crystal silicon (approximate 190 GPa) is not necessarily problematic [15].

Stiffener array increases moment of inertia (and bending stiffness); bending stiffness is product of Young's modulus and moment of inertia [16]. Silicon (approximate 0.17 Poisson's ratio) will resist biaxial strain in presence of normal load [17]. Although silicon is, by definition, a brittle material (does not yield prior to fracture), fracture strength (approximate 7000 MPa, maximum) far exceeds pressure-induced stresses [15,17]. Silicon has a high thermal conductivity (157 $W \cdot m^{-1} \cdot K^{-1}$), facilitating efficient heat flux (conductive heat transfer) relative to bulk thermal gradient, as per Fourier's Law ($q=-k\nabla T$) [15,18]. Low coefficient of linear thermal expansion (2.33E-06 K^{-1}) mitigates possible crack initiation/propagation resultant from cyclic thermal shock [15,19].

Intrinsic surface (unetched posterior) of the window is in direct contact with the excimer gas of 0.08 psi diatomic fluorine partial pressure (approximate 0.5%, molar) [2]. Fluorine has the highest standard oxidation potential (+2.866 eV) of all elements [20]. Contact with silicon results in spontaneous fluorination (silicon tetrafluoride (SiF_4), gas phase), as per a negative Gibbs free-energy change, equilibrium constant greater than unity, and positive net potential [21]. Hydrofluoric acid (HF), produced from reaction of hydro-compounds (i.e. ambient moisture) with fluorine free-radicals, may also be present (trace element) in the excimer gas cavity (extremely corrosive to silicon) [2]. Deposition (physical methodology) of a silicon nitride (Si_3N_4) passivation layer (approximate 500 nm) onto the exposed silicon surface mitigates interaction with reactive species [22]. Further investigation will be performed to grow (chemical methodology) thin-film Si_3N_4 directly into crystalline matrix of window [23]. The process will create a thin-film passivation layer (approximate 8 nm) having no definitive interface with the silicon, such that shear deformation (film cracking and/or delamination), resultant from divergent coefficients of thermal expansion, does not (significantly) occur [23].

Collisions between accelerated electrons and material, resulting in energy and momentum transfer phenomena, yield the highest percentage transmission loss from beam emission cathode to excimer gas cavity [24]. Collision energy loss is dependant upon material parameters (i.e. density, charge-to-mass ratio, mean excitation energy, traverse thickness), and relativistic parameters of incident electrons [25]. Quantity is computed from the theory of Bethe (1930, 1932), with a density-effect correction evaluated according to Sternheimer (1952, 1982) [12,26]. Other effects (i.e. multiple scattering (and backscattering), radiation yield/loss, bremsstrahlung, etc.) contribute to moderate losses in transmission, and must also be considered [25].

Material composition and dimensions must be correlated to accommodate greater than 80% beam transmission efficiency (750 keV), as per energy requirements for excited dimer formation [2].

Effect of relativistic electron bombardment on the window has also been considered [27]. High-energy electron beams (500 keV to 10 MeV) may alter electrical properties of silicon and/or cause sputtering at the exit surface [27]. However, the sputtering rate is relatively low and should not affect structural behavior of the window [27]. At lower temperatures (less than 50 K), associated changes in entropy result in disruption of crystal lattice (i.e. amorphous transition); this phenomenon becomes insubstantial at temperatures exceeding 300 K [27]. The window will be subject to high-energy magnetic field(s) used to shape/partition the electron beam; these are not potential issues (silicon is a diamagnetic material) [2,28].

IV. HEAT TRANSFER OPTIONS

The repetitive high-energy pulsed power of electron beam diodes (as drivers for IFE devices) is attenuated, resulting in a fractional loss of energy that is inadvertently transferred to the windows [2]. This energy is dissipated as heat energy (sensible heat), generating a temperature increase (per pulse) relative to the mass specific heat capacity (a function of bulk temperature) of the substrate

[2]. The corresponding thermal expansion produces residual (thermal) stress in the substrate [29]. Accumulation of residual stress in the substrate reduces fatigue life via (increased probability for) crack initiation and propagation [29]. The requirement for electron beam transmission window fatigue life in Electra (1.0E+05 shots) make it necessary to investigate mechanism(s) for active cooling of the interface structure [2].

Temperature increase is calculated to be approximate 30ºC (303 K) per pulse, assuming no heat transfer to surroundings via conduction and/or convection [2]. Taking into consideration the sensible heat loss (continuous over actual shot and delay time between shots) to the active medium via forced convection, the actual temperature rise will be much less [18]. Integrating this temperature increase over many pulses, the steady state temperature (maximum) that the silicon window will encounter can be calculated [8]. This temperature should be at a value imparting minimum quantity of stress concentrations within the window [8]. Additional methods of heat transfer must therefore be considered (total power allocated to heat transfer must be less than 2.5% of total system power) [2].

Heat transfer via (external) evaporative cooling has been considered as a feasible solution for thermal stress reduction and heat removal in the window

[30]. Employment of this method would require machined channels within the metal support framework, and an additional membrane interface to enclose the spray cooled area [30]. The tubes would, in practice, deliver a low vapor pressure coolant to spray nozzles, positioned such that all internal surfaces receive an even distribution of the coolant [30,31]. Vapor would be evacuated from the enclosed area via a vacuum pump prior to each pulse [30,31]. The system would be configured such that the effluent vapor would pass through a condenser and/or compressor for recycle as liquid coolant (closed system) [32]. The obvious disadvantage with this heat transfer method is the addition of a second membrane, which could impede electron beam transmission [2,24]. Deposition of non-evaporating impurities (possibly incorporated into the chemical composition of coolant) onto the surface of the window could also contribute to transmission reduction, and could add stress to the window [2,10]. Required power input for this heat transfer method is large relative to the heat rejected from the window surface, since much of the power is allocated to the recovery system operation [32].

Edge-cooling has been considered as another feasible solution for thermal stress reduction and heat removal in the window [2]. Thermal energy accumulation (after many pulses) would reach its maximum value at a position local to the (bulk) center of the window, and would be surrounded by a quasi-elliptical thermal profile [7]. Applying a heat sink to the outer edge of the window, via internal refrigerant flow through the metal support framework, would establish a differential temperature gradient between the outer edge and bulk of the window [2]. Heat energy would be displaced from the bulk to the outer edge, and consequently be rejected to the heat sink [2]. The likely refrigerant for this type of active cooling would be water, which could be cooled (for recycle) by cooling tower or chiller process at relatively low power input [2]. However, power requirement for feed supply pump could be of concern, as this method of heat transfer generally would require a large flow rate to provide adequate cooling efficiency [32].

The heat transfer method currently of interest to PPPL is employment of a solid-state heat pump to reject heat via thermoelectric (Peltier) cooling effect [33]. This process is an expansion upon the aforementioned edge-cooling concept, in that heat energy would be displaced to the outer edge of the window for rejection to internal cooling channels (or other heat sink) within the metal support framework [2]. The governing principle of the Peltier effect is the passage of a DC current between two dissimilar materials, through a semiconductor junction, to cause a temperature differential (P and N doping of semiconductor would replace need for dissimilar materials) [33]. Consequently, heat energy is absorbed at one interface and discharged at the other [33]. Application of this technology to the window configuration would be accomplished via passage of current through the silicon window from one side of the metal framework to the other [33]. Polarity of the current could be reversed to change direction of heat flux; this would serve as a preventative measure for disproportionate loading of edges [33]. Implementing a solid-state heat pump could mitigate the dependence upon coolant/refrigerant liquids, which would require additional power to process the effluent [33].

V. PRESENTATION OF EMPIRICAL RESULTS

The inherent task was to develop silicon-based electron beam transmission windows for use in an ICF evaluation program [34]. These windows were subjected to conditions in simulation of that expected throughout the course of operations of the Electra ICF laser facility, at the Naval Research Laboratory (NRL) [2]. The design process entails compilation of parameters/requirements database, system modeling (i.e. electron transport and material behavior), fabrication of prototypes, and empirical analysis is therefore necessary for design verification [7,12,13]. Preliminary bench top testing has indicated that the silicon window can withstand a monotonic pressure differential of approximately 1.5 atm, and can endure repetitive (5 repetitions per second) cycling of approximately 0.3 atm amplitude. Silicon (first-generation prototype) permitted electron beam transmission of 69% ± 5% [35]. Further research will be conducted to establish justification (within acceptable confidence interval) for silicon as a feasible material. Additional heat transfer options will also be explored [2].

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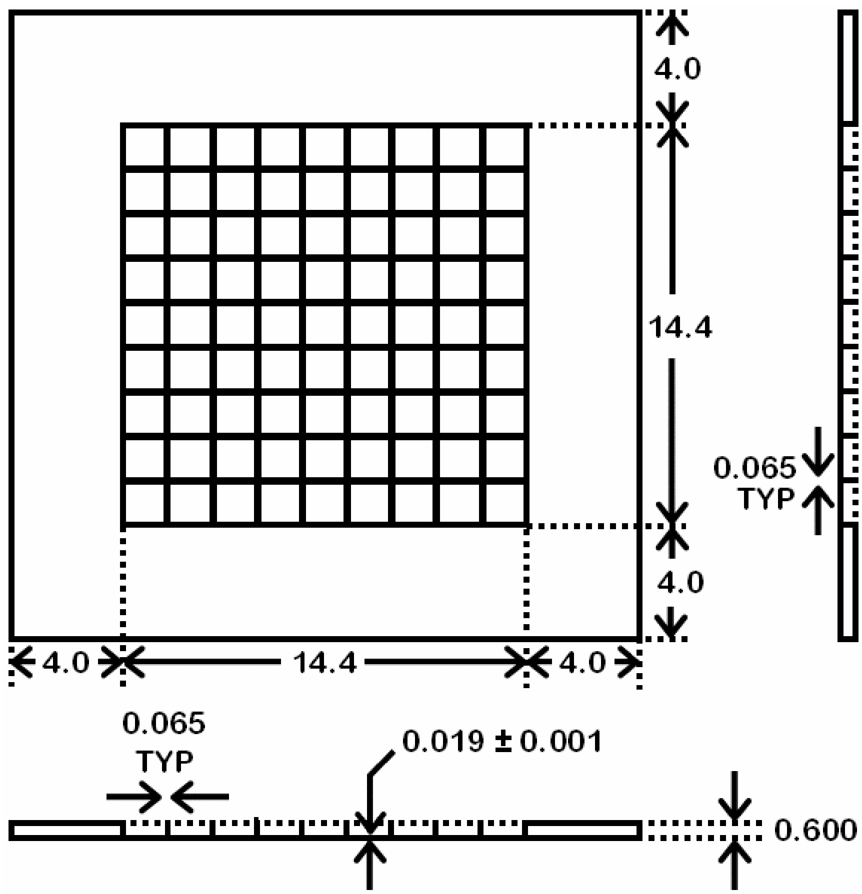

FIG. 1. Drawing shows silicon-based electron beam window configuration, as per PPPL second generation prototype design. All dimensions are in millimeters; "TYP" indicates typical dimension. Tolerance equals ± 0.01, unless otherwise indicated. Passivation layer (500 nm thin-film Si_3N_4) not shown.

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