slightly greater than the 8-GHz free spectral range of the spectrum analyzer. The width at half-intensity is 5.5 GHz.

In conclusion, we have reported mode-locked ultraviolet pulses of 200-psec duration at 10-mW average power. The operation is stable and may be considered another useful property of the argon ion laser as a spectroscopic tool. Remeasurement of the visible lines yields pulse durations shorter (and oscillating bandwidth larger) than previously reported. While some of the discrepancy between the present and previous pulse-duration measurements may be due to different electronic instrumentation, we feel that improvement in ion laser construction leading to higher gain (and consequent greater bandwidth) is a factor.

FIG. 4. Oscilloscope trace of the mode-locked optical frequency spectrum for the 5145-Å line. The axial mode spectrum is shown under multiple pulsing operation. The modes are separated by 88 MHz and the dispersion is 1.23 GHz/div. The optical spectrum analyzer has free spectral range of 8 GHz and the total oscillating bandwidth is slightly larger (about 9 GHz).

5145-Å line. The FWHM is 170 psec. Figure 4 is an oscilloscope photograph of the optical frequency spectrum analyzer display when the laser is mode locked (multiple pulsing) on the 5145-Å line. The total oscillating bandwidth is approximately 9 GHz.

DIRECT OBSERVATION OF LONG-RANGE MIGRATION OF SELF-INTERSTITIAL ATOMS IN STAGE I OF IRRADIATED PLATINUM

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The motion of single self-interstitial atoms (SIA's) in stage I of irradiated platinum was observed directly by field ion microscopy. A specimen irradiated at a temperature of 10 K with 20-kV Pt ions was found to contain immobile SIA's in the bulk at this temperature, as determined via pulse-field evaporation experiments. Direct observation of specimens, irradiated with 20- or 30-kV Pt ions, during warming experiments from 10 to 70 K showed that a flux of SIA's crossed the surface of the specimens between 13 and 25 K. Application of a diffusion model to the data yielded a value of \( \sim 0.06 \) eV for the enthalpy change of migration and a diffusion coefficient of \( \sim 0.5 \text{exp}(-0.06 \text{ eV}/kT) \text{cm}^2 \text{sec}^{-1} \) for the SIA.

In this letter we present direct evidence for long-range migration of a self-interstitial atom (SIA) in stage I (0 to 35 K) of platinum which was irradiated with 20- or 30-kV Pt ions. Platinum specimens were irradiated in situ under ultrahigh vacuum conditions, and both the initial state of damage and the recovery behavior of the SIA's produced by the irradiation were determined by field ion microscopy. At a tip temperature (\( T_\tau \)) of \( \leq 13 \) K the initial state of damage consisted of depleted zones, elongated voids, dislocation loops, and a distribution of immobile SIA's which very probably originated at the depleted zones. Annealing experiments between 10 and 70 K showed that these SIA's became mobile between 13 and 25 K.

The specimens for the irradiations were prepared from 0.0127-cm-diam wires with a resistivity ratio \( R \sim R_{290} \) of greater than \( 3 \times 10^7 \). These specimens were irradiated in situ at a pressure of \( \leq 8 \times 10^{-10} \) Torr in a bakeable field ion microscope (FIM) which was connected to a sputter ion source via a differential pumping system. Pt ions were used for the irradiations in order to avoid the introduction of any impurities during the bombardment. The FIM images were recorded on 35-mm film employing a ciné camera with the aid of an internal intensification system based on a 76-mm channel plate. For the annealing experiments the \( T_\tau \) was increased in steps of 2 K, and maintained at each \( T_\tau \) for 6 min (this corresponds to an average linear warming rate

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\( \sim 2.2 \times 10^{-5} \) atom fraction. This observation also showed that the imaging electric field \( E \approx 4 \) to \( 5 V(\AA)^{-1} \) had not caused a stressed-induced migration of SIA's at \( 13 \) \( ^{\circ} \text{K} \) as a result of a lowering of the enthalpy change of migration \( (\Delta H_{\text{m}}^\circ) \).\(^3\)

The results of the second series of experiments are given in Fig. 1 which shows a histogram of the fraction of the total number of SIA's which crossed the specimen's surface per \( 1 \) \( ^{\circ} \text{K} \) as a function of \( T \). during the annealing experiments. A total of 47 SIA's were found in four different experiments. These 47 SIA's were detected as a result of scanning 11990 frames of 35-mm cine film. In addition, 6490 frames of control film from recovery experiments on two unirradiated specimens were scanned and no contrast effects which could be attributed to SIA's were detected. All of the SIA's which crossed the surface of the specimen exhibited a simple bright spot type of contrast.\(^1,4,5\) Two different examples of this contrast effect are shown in Fig. 2. The arrows in this figure point to either the points where the SIA's will emerge, or to the SIA's once they have emerged. The approximate envelope of this experimental histogram exhibited a maximum at \( -23 \) \( ^{\circ} \text{K} \), and had a width at half-maximum of \( -8 \) \( ^{\circ} \text{K} \). At \( 23 \) \( ^{\circ} \text{K} \), SIA's were observed to cross the surface as a function of time. The times measured were consistent with the SIA's migrating from a depth of \( -120 \) \( \AA \) (the calculation was made with the SIA diffusion coefficient obtained from the model described below). This was further proof that SIA's undergo long-range migration at this temperature.

The calculated peak shown in Fig. 1 was obtained from a diffusion model\(^3\) based on the following assumptions: (1) The surface was the dominant sink for SIA's;\(^1,4,5\) (2) the diffusion of SIA's occurred via a single thermally activated process; (3) the shape of the tip was approximated by a sphere of radius \( R \); (4) the initial distribution of SIA's was uniform; and (5) there was no clustering of SIA's or SIA-impurity atom complexes formed during the anneal. The ex-

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**FIG. 1.** A plot of the fraction of the total number of SIA's per \( 1 \) \( ^{\circ} \text{K} \) as a function of the annealing temperature \( (^{\circ} \text{K}) \). The average radius \( R \) was \( 250 \) \( \AA \) for four different specimens which were irradiated to doses between \( (2-8) \times 10^{14} \text{ Pt}^{+} \text{ ion cm}^{-2} \).

\( o \) of \( (1/3) \) \( ^{\circ} \text{K min}^{-1} \), while the surface was photographed continuously at a rate of \( 1 \) frame sec\(^{-1} \).

The first result is that immobile SIA's were found in the bulk of a specimen which was irradiated at \( 10 \) \( ^{\circ} \text{K} \) to a dose of \( 7 \times 10^{14} \text{ ion cm}^{-2} \) and then pulse field evaporated at \( 13 \) \( ^{\circ} \text{K} \). The distribution of SIA's found was uniform to a depth of \( \sim 130 \) \( \AA \) from the surface of this specimen, and the SIA concentration was

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**FIG. 2.** The appearance of SIA's during an anneal at (a) 19, (b) 21, and (c) 23\( ^{\circ} \text{K} \) in a specimen irradiated at \( 11 \) \( ^{\circ} \text{K} \) to a dose of \( 2 \times 10^{14} \text{ ion cm}^{-2} \) with 30-keV Pt\(^{+} \).
pression for the flux of SIA’s \( J_{11} \) crossing the surface as a function of \( T \) obtained from this model was

\[
J_{11} = \beta \exp(-1/y) \sum_{n=1}^{\infty} \exp[-n^2 \Gamma y^2 \exp(-1/y)],
\]

where \( y = kT/\Delta H_{11}^m \), \( \Gamma \) is \( \pi^2 D_0^0 \Delta H_{11}^m / R^2 \alpha k \) (these two parameters are dimensionless), and \( \beta \) is \( \xi^2 \Omega c_0^0 D_1^0 \). The quantity \( D_0^0 \) is the pre-exponential factor of the SIA diffusion coefficient, \( c_0^0 \) the initial concentration of SIA’s, \( \xi \) is the fraction of the total area of the sphere which was observed, and \( k \) is Boltzmann’s constant. The calculated peak shape superimposed best on the experimental histogram for \( \Gamma \) equal to \( 10^{17} \). This fit implied that \( \Delta H_{11}^m \) was \( \sim 0.06 \) eV, and that \( D_0^0 \) was \( \sim 0.5 \) cm\(^2\) sec\(^{-1}\). For a given value of \( \Gamma \) the experimental maximum determined \( \Delta H_{11}^m \), and then \( D_0^0 \) was obtained from the relationship \( D_0^0 = \Gamma R^2 \alpha k / 8 \pi^2 \Delta H_{11}^m \). We note that the calculated peak width at half-maximum was 2.5 K, which was a factor of 3.2 smaller than the experimental value of \( \sim 8 \) K. This small factor could have been caused by the clumping of SIA’s, impurity-SIA cluster formation, or pressure gradients in the specimen. This point has already been discussed qualitatively\(^3\) and it will be considered in more detail in the future.

There exists extensive literature on the recovery behavior of Pt irradiated with thermal neutrons, fast neutrons, deuterons, and electrons (see Schilling et al.\(^8\) for a review). In particular, Bauer and Goepfinger\(^7\) measured an activation energy of 0.065 ± 0.005 eV for the recovery of electron irradiated Pt between 24.2 and 28.2 K, while Herschbach and Jackson\(^8\) measured a spectrum of activation energies ranging from 0.06 to 0.07 eV between 21 and 24 K. The measured quantity \( \Delta H_{11}^m \) in the present experiment is given by

\[
\Delta H_{11}^m = \Delta U_{11}^m - (E^2/8\pi) \Delta V_{11}^m,
\]

where \( \Delta U_{11}^m \) is the internal energy change of migration of SIA, \( \Delta V_{11}^m \) is the volume change of migration of a SIA, and \( E^2/8\pi \) is the maximum value of the negative hydrostatic pressure due to \( E \). In the macroscopic recovery experiments the measured activation energies are approximately equal to \( \Delta U_{11}^m \). The upper limit to \( \Delta V_{11}^m \) was, therefore, \( \leq 0.02 \) atomic volume (via Eq. 1). This value was obtained by using our \( \Delta H_{11}^m \) and the values of \( \Delta H_{11}^m \) determined from the resistivity recovery experiments. Thus the present experiments constitute the first direct quantitative correlation between a FIM recovery spectrum and the recovery spectra of radiation-induced resistivity changes in stage I of Pt.

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ELECTROREFLECTANCE AND THERMOREFLECTANCE OF ZnSiAs\(_2\)\(^†\)

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Measurements of electroreflectance as a function of temperature in the range 195—350 K and of thermoreflectance at room temperature have been made on chalcopyrite-type ZnSiAs\(_2\) in the energy range 1.9—3.5 eV. The identification of the various peaks in the \( E_0 \) and \( E_1 \) complexes is discussed and the temperature coefficient of the various transitions determined.

Recently, various room-temperature electroreflectance (ER) measurements have been made on chalcopyrite-type ZnSiAs\(_2\) in the energy range 1.5—6.0 eV using the electrolyte method\(^1,2\) and different interpretations of the data in the \( E_0 \) and \( E_1 \) regions of the spectrum suggested. Therefore, further modulated reflectance work is of interest to clarify the situation. In the present work, we report ER and TR (thermoreflectance) measurements on this compound in the energy range 1.9—3.5 eV, the ER measurements being made at temperatures in the range 195—350 K using a dry-sandwich metal—insulator—semiconductor configuration, and the TR measurements made at room temperature with an indirect heating method.

The samples used in this work were \( p \)-type crystals grown by the Bridgman method, having room-temperature hole concentrations of \( 2 \times 10^{15} \) cm\(^{-3}\). The